Energy and Buildings 103 (2015) 414–419

Contents lists available at ScienceDirect

Energy and Buildings

journal homepage: www.elsevier.com/locate/enbuild

Engineering advance

Phase change materials and thermal energy storage for buildings☆

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ARTICLE INFO

Article history:
Available online 10 June 2015

Keywords:
Thermal energy storage (TES)
Buildings
Sensible heat storage
Latent heat storage
Passive
Active

ABSTRACT

It is well known that there is a need to develop technologies to achieve thermal comfort in buildings lowering the cooling and heating demand. Research has shown that thermal energy storage (TES) is a way to do so, but also other purposes can be pursued when using TES in buildings, such as peak shaving or increase of energy efficiency in HVAC systems. This paper reviews TES in buildings using sensible, latent heat and thermochemical energy storage. Sustainable heating and cooling with TES in buildings can be achieved through passive systems in building envelopes, Phase Change Materials (PCM) in active systems, sorption systems, and seasonal storage.

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1. Introduction

It is well known that the use of adequate thermal energy storage (TES) systems in the building and industrial sector presents high potential in energy conservation [1]. The use of TES can overcome the lack of coincidence between the energy supply and its demand; its application in active and passive systems allows the use of waste energy, peak load shifting strategies, and rational use of thermal energy [2]. Advantages of using TES in an energy system are the increase of the overall efficiency and better reliability, but it can also lead to better economics, reducing investment and running costs, and less pollution of the environment and less CO_2 emissions [3].

Storage concepts applied to the building sector have been classified as active or passive systems [4]. Passive TES systems can enhance effectively the naturally available heat energy sources in order to maintain the comfort conditions in buildings and minimize the use of mechanically assisted heating or cooling systems [5]. These systems include increased use of ventilated facades [6], thermal mass [7,8], shading effect using blinds [9], coated glazing elements [10], and solar heating and free cooling (night ventilation) techniques [11].

On the other hand, the use of active TES systems provides a high degree of control of the indoor conditions and improves the way of storing heat energy. These systems are usually integrated in buildings to provide free cooling or to shift the thermal load from on-peak to off-peak conditions in several applications, such as domestic hot water applications [12] or HVAC systems [13,14].

The present paper will review the existing and explored active and passive TES technologies integrated in the building sector, as well as the materials developed and used in these systems.

2. Materials used for TES in buildings

High energy storage density and high power capacity for charging and discharging are desirable properties of any storage

☆ This is an engineering advance paper.
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http://dx.doi.org/10.1016/j.enbuild.2015.06.007
0378-7788/

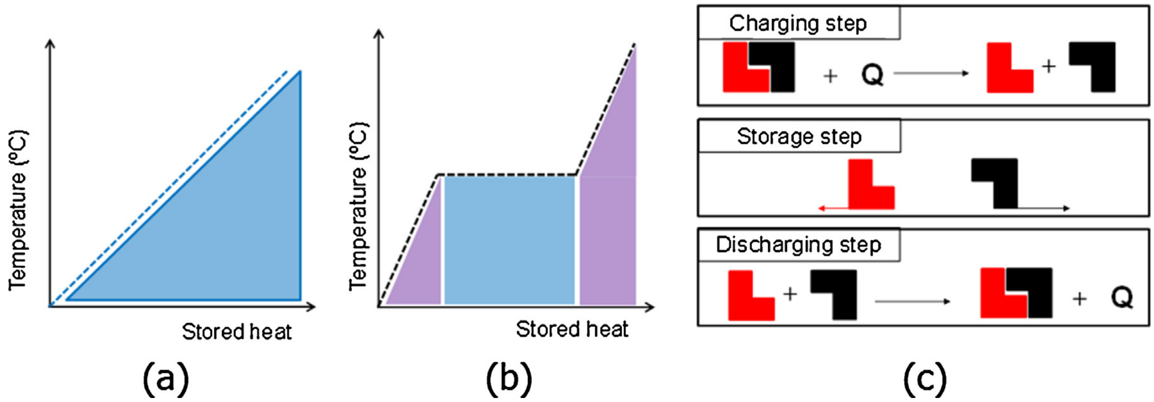

Fig. 1. Methods of thermal energy storage. (a) Sensible heat, (b) latent heat, (c) thermochemical reaction.

system. It is well known that there are three methods of TES: sensible, latent, and thermochemical energy storage (Fig. 1).

Sensible heat (Fig. 1a) is the simplest method to store thermal energy and consists of applying a temperature gradient to a media (solid or liquid) in order to accumulate or release heat. The most common material used to store energy as sensible heat is water. Moreover, certain materials based on common ceramics (cement, concrete, etc.), some natural stones like marble, granite, clay, sandstone, and polymers (PUR, PS, PVC) are also widely used. Thereby, waste materials from several industrial processes with proper thermophysical properties are becoming suitable candidates to be used for sensible heat TES [15,16•].

Sensible heat storage has two main advantages: it is cheap and without the risks derived from the use of toxic materials. Moreover, the material used to store energy is contained in vessels as bulk material, thereby facilitating the system design. The main drawback of the application of sensible heat storage in the building sector is the high volume that it would require depending on the amount of desired heat stored from the active or passive technology [18•].

The energy storage density increases and hence the volume is reduced, in the case of latent heat storage (Fig. 1b) [18•]. The incorporation of phase change materials (PCM) in the building sector has been widely investigated by several researchers [17,18•]. PCM are classified as different groups depending on the material nature (paraffin, fatty acids, salt hydrates, etc.). Each material presents their own advantages and limitations, so its selection has to be done based on the application requirements. Paraffins and fatty acids present no subcooling, low hysteresis and are more stable than the salt hydrate which can present segregation after cycling [19]. The main disadvantages of the paraffins and fatty acids are their low thermal conductivity, which might be enhanced using thin encapsulation, maximizing the heat transfer area or using a graphite-matrix [20••]. Moreover, the prevention of fire hazards has to be considered when using these materials, therefore recently the addition of fire retardants has been investigated [21].

These materials make use of the latent heat between the solid and liquid phase change, and must be encapsulated or stabilized for a technical use in any building systems, either active or passive. Thus can be achieved using a direct inclusion in the wall [22], by impregnation in a porous material as gypsum [23], by using microencapsulation techniques [24], using a shape-stabilization [25] or slurries of PCM suspended on a thermal fluid [26•]. The encapsulation is a key issue for the implementation of these technologies in the buildings and must be designed to avoid leakage and corrosion.

Finally, the thermochemical materials (TCM) store and release heat by a reversible endothermic/exothermic reaction process (Fig. 1c). During the charging process, heat is applied to the material A, resulting in a separation of two parts B + C. The resulting reaction products can be easily separated and stored until the discharge process is required. Then, the two parts B + C are mixed at a suitable pressure and temperature conditions and energy is released. Even though this method is the most energy-efficient, they are under developing phase and there are no real applications implemented in the building sector [27•]. Within this context, this technology has to overcome important barriers such as corrosion, poor heat and mass transfer performance and materials development [28]. The high energy density of these processes and the lack of heat gains or losses during the

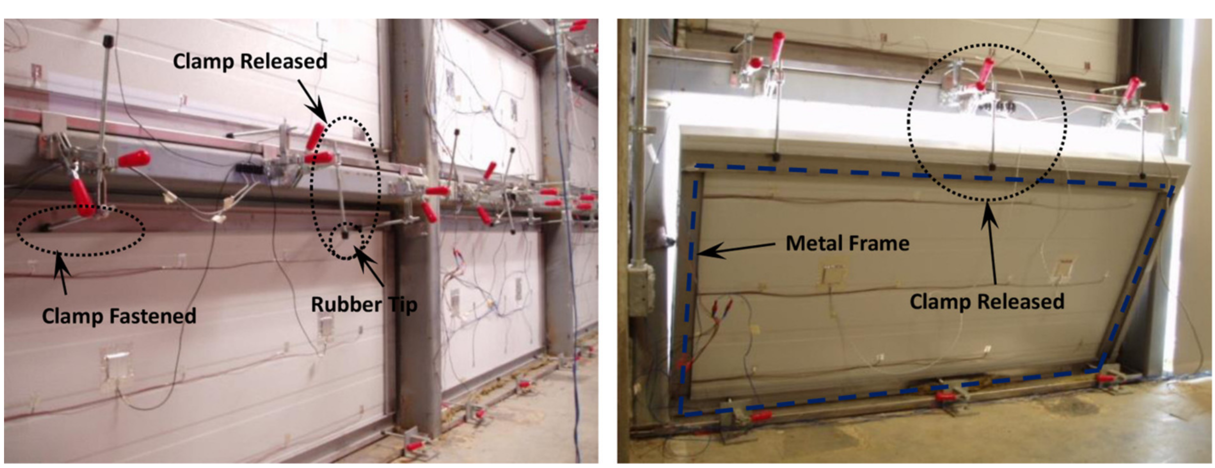

Fig. 2. So-called plug-and-play testing site for PCM containing wallboards [34].

storage period, makes the method suitable for seasonal storage applications.

3. Passive technologies

The use of TES as passive technology has the objective to provide thermal comfort with the minimum use of HVAC energy [29]. When high thermal mass materials are used in buildings, passive sensible storage is the technology that allows the storage of high quantity of energy, giving thermal stability inside the building. Materials typically used are rammed earth, alveolar bricks, concrete, or stone [30].

Standard solar walls, also known as Trombe walls, and solar water walls also use sensible storage to achieve energy savings in buildings [31,32]. Solar water walls follow the same principle as the standard ones, but the massive part of it is replaced by water containers forming the wall.

Much more attention has been paid in the literature to passive thermal energy storage using phase change materials. PCM can be incorporated in construction materials using different methods, such as direct incorporation, immersion, encapsulation, micro-encapsulation and shape-stabilization [33]. In direct incorporation and immersion potential leakage has to be assessed. When the PCM is encapsulated or added in a shape-stabilized new material, a new layer appears in the construction system of the wall.

Traditionally, wallboards have been studied as one of the best options to incorporate PCM to building walls. Recently, Lee et al. [34] highlighted the importance of experimental validation of wallboards and its long time duration. To reduce this duration, the authors presented a new testing concept with high flexibility that allows testing different wall systems in real time (Fig. 2).

A new approach in PCM-wallboards is the addition of the PCM supported by expanded graphite nanosheets to improve its thermal conductivity with the aim enhanced thermal storage and energy distribution (Fig. 3) [35]. The same objective was pursued with the addition of an aluminium honeycomb in a containing microencapsulated PCM wallboard (Fig. 4) [36].

Similarly, PCM can also be impregnated or mixed with concrete [37] or mortar [37,38]. One of the objectives pursued here is to maintain the concrete mechanical properties, while increasing its specific heat capacity. It is interesting to highlight that the addition of PCM in concrete decreases its density, which would have an interesting impact in the building structure weight.

Another approach to incorporate PCM in building walls is it mixture with insulation materials. This concept has been reviewed by Yang et al. [39], who showed that the joint advantages of the storage capacity of PCM and the insulation performance of polyurethane foams has a great potential to promote energy efficiency in buildings, but still research is needed to improve this composite. Until now, studies mainly focus on synthesis methods

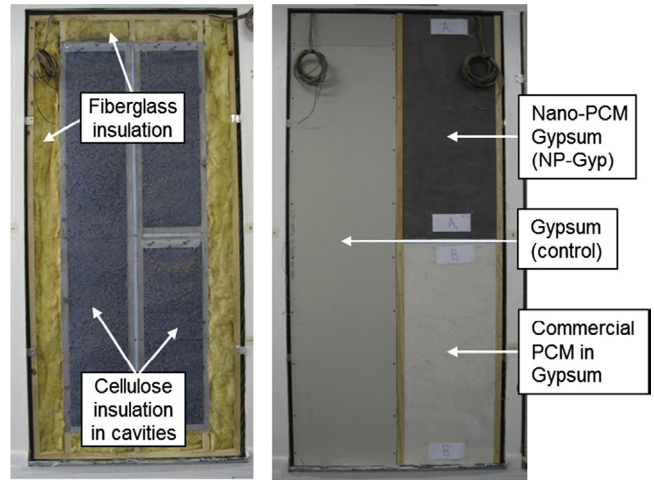

Fig. 3. Test wall with PCM-enhanced wallboards [35].

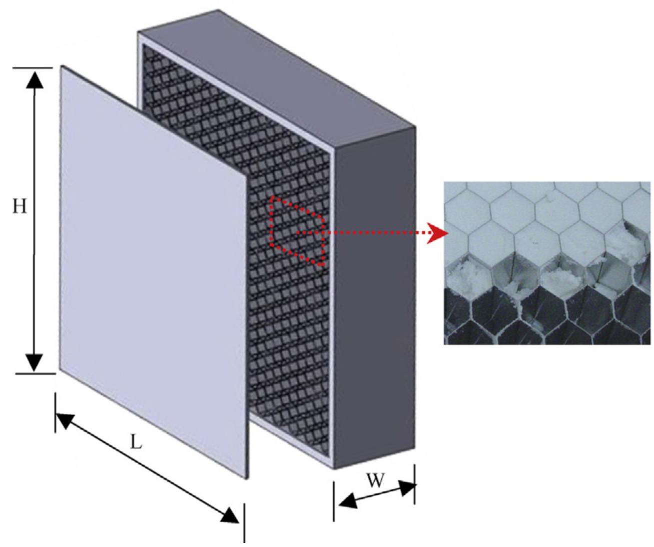

Fig. 4. Microencapsulated PCM honeycomb wallboard [36].

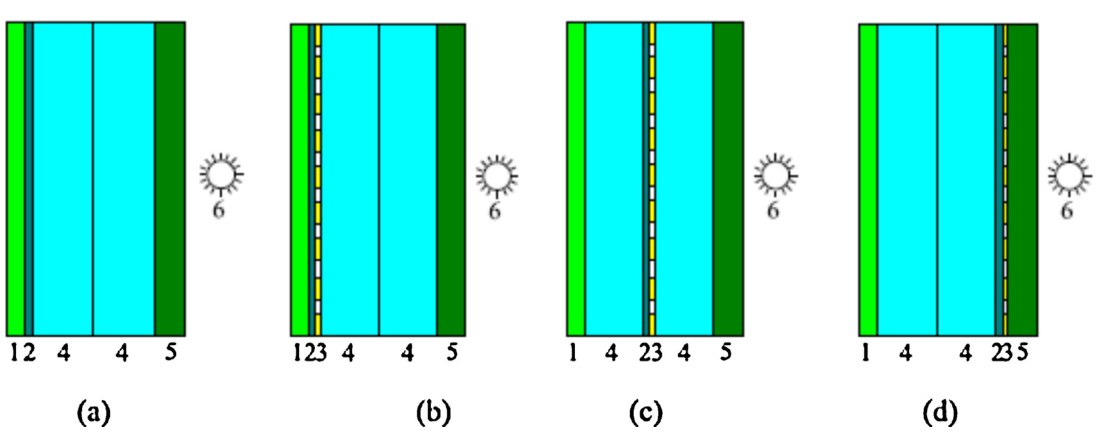

Fig. 5. Wall including PCM in different locations: (a) control wall; (b) PCM located next to the internal face of a gypsum wallboard; (c) PCM located between two insulation layers; and (d) PCM located next to the internal face of an oriented strand board [40].

Fig. 6. Clay bricks including PCM macrocapsules [41].

and TES capacity but omit some important parameters, especially heat transfer resistance, which is the most important for thermal insulating materials.

When PCM is added encapsulated, in bigger enclosures than microencapsulation, the location of the PCM within the building is of big importance for the optimum performance of the system. Fig. 5 shows different locations in a typical lightweight building construction system [40]. In masonry wall, the PCM incorporation can be, for example, within clay bricks (Fig. 6) [41].

4. Active technologies

The use of TES in building active systems is an attractive and versatile solution for several applications for new or retrofitted buildings, such as the implementation of renewable energy sources in the HVAC for space heating and/or cooling, the improvement in the performance of the current installations or the possible application of peak load shifting strategies [42].

The integration of the TES in the building can be done using the core of the building (core, floor, walls), in external solar facades, in suspended ceilings, ventilation system, PV systems and water tanks, as shown in Fig. 7.

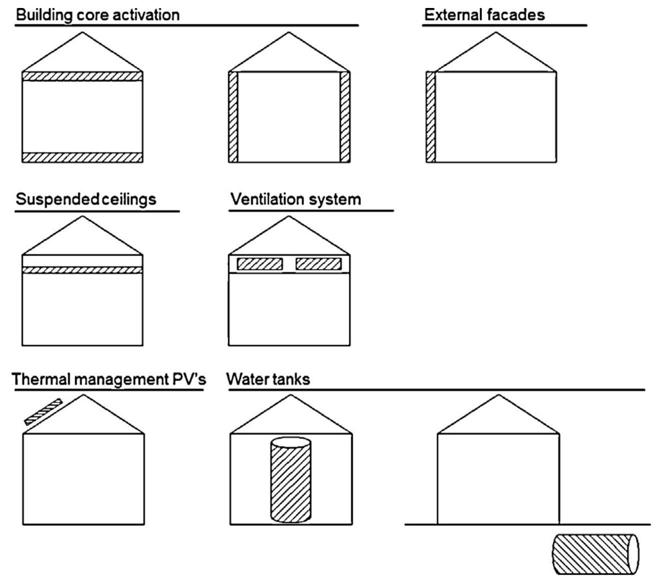

Fig. 7. Integration of the TES in buildings.

One of the main applications of TES in active building systems is the use of free cooling, when the storage is charged with low night outdoor temperatures and this stored cold is discharged when required by the cooling demand [43]. Here, since there is a small gap between the cold source and the application (building comfort), the use of PCM as the storage medium is recommended because of its high energy density within the phase change. The main barrier that this technology is facing is the difficulty of ensuring the full solidification of the PCM in certain climates or summer periods, in which the temperature do not drop enough time below the phase change range. This issue can be overcome enhancing the thermal conductivity of the PCM and using appropriate control strategies. Several systems have implemented TES for free cooling purposes, such as thermally activated building systems (TABS) [44], suspended ceilings [45] (Fig. 8), external facades [46] or in the ventilation system [47].

Furthermore, TES have been used in building solar systems in order to convert an intermittent energy source and meet the heating and domestic hot water demand (usually also intermittent but at different periods of time) [48]. The most popular solar thermal energy storage is the use of water tanks. Because of the high volume they occupy, their integration into the building has been recently addressed. This integration has been done by architecturally including the storage in the living areas or by using ground integrated tanks. The use of underground storage is justified if seasonal thermal energy storage strategies are considered [49]. Moreover, the thermal energy storage of solar energy in active building systems is extended to integrate solar air collectors in building walls [50] or use PCM in ventilated facades [51] (Fig. 9).

As it was previously stated, the use of active TES systems in the building sector is not limited to the implementation of renewable sources, but to increase the efficiency and performance of already

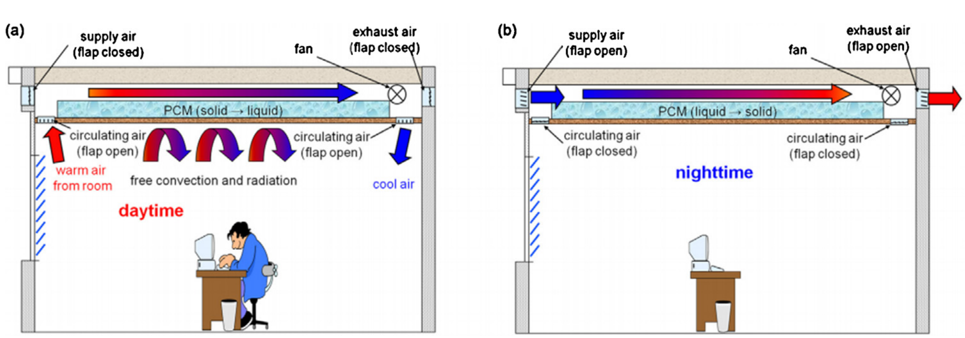

Fig. 8. Cooling (a) and regeneration mode (b) of the ventilated cooling ceiling with PCM [45].

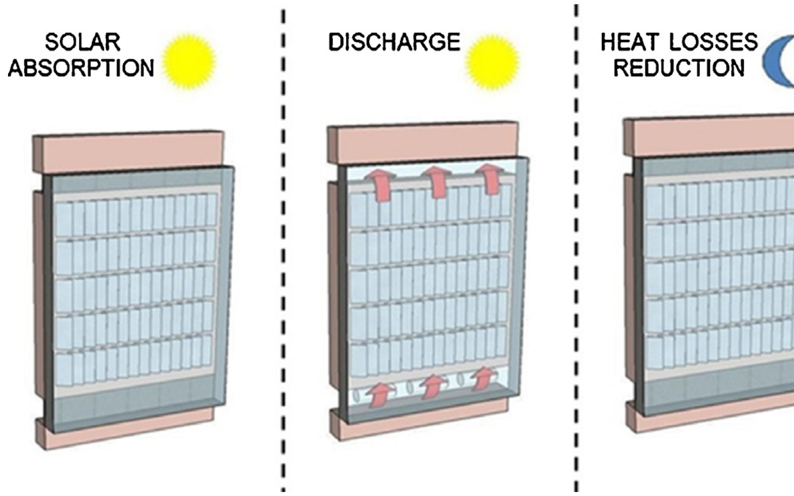

Fig. 9. Operational mode of the ventilated facade with PCM [51].

existing technologies. Within this context, the utilization of heat pumps with TES systems are presented as a promising technology to shift electrical loads from high-peak to off-peak periods, thus serving as a powerful tool in demand-side management [52]. The benefits of this technology are focused on the energy cost savings by using thermal energy stored during low-cost electricity tariff. The incorporation of these systems in the buildings has been investigated both for space heating and cooling. The TES is implemented in the heat pumps not only for load shifting but for achieve important energy savings on the defrosting system of the outdoor unit or for heat recovery applications, as well [53].

The incorporation of any of the previous cited TES technologies, in active systems in the building design, requires smart control techniques that could enhance the performance of these costly systems and make them attractive to architects and engineers.

5. Conclusions

The present paper is a state of the art of the studied active and passive TES technologies integrated in the building sector. It also highlights the main advantages and drawbacks of each technology, including the materials used for sensible, latent and thermochemical heat storage.

Regarding passive technologies, which are used to maintain a thermal stability and to reduce the use of active heating and cooling devices, sensible heat storage has been introduced in Trombe and solar water walls. However, the use of PCM has been further investigated so they do not require high volume, which is normally a limitation in the building sector. Important design considerations have to be taken into account if using PCM for passive cooling, such as thermal stability or leakage.

Furthermore, the inclusion of TES in active systems has been investigated for the implementation of renewable energies for space heating and/or cooling, for improving the performance of the current installations and for using peak load shifting strategies. The integration of the storage has been done in the core of the building, external facades, suspended ceilings, ventilation system, or water tanks. The high cost of these technologies, makes crucial the use of smart control techniques in order to enhance their performance and make them cost-effective.

TES has very big potential as a key technology to reduce the energy demand of buildings and/or to improve the energy efficiency of their energy systems. Several groups and associations (i.e. IEA, RHC Platform, EASE) have highlighted this potential and have even given the points that need to be further studied to achieve this potential. Some of these challenges are to reduce the cost, to increase the compactness of the systems, to increase the energy density of the materials and systems, to increase the thermal conductivity of the materials, and to develop new materials, especially fluids that can act as heat transfer fluids and storage material at the same time.

Acknowledgements

The work partially funded by the Spanish government (ENE2011-22722 and ULLE10-4E-1305). The authors would like to thank the Catalan Government for the quality accreditation given to their research group (2014 SGR 123). The research leading to these results has received funding from the European Union's Seventh Framework Programme (FP7/2007-2013) under grant agreement no. PIRSES-GA-2013-610692 (INNOSTORAGE). Alvaro de Gracia would like to thank Education Ministry of Chile for Grant PMI ANT1201.

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