Applied Energy 202 (2017) 420–434

Contents lists available at ScienceDirect

Applied Energy

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

Simulation-based optimization of PCM melting temperature to improve the energy performance in buildings

Mohammad Saffari [a], Alvaro de Gracia [b], Cèsar Fernández [c], Luisa F. Cabeza [a,*]

[a] GREA Innovació Concurrent, INSPIRES Research Centre, University of Lleida, Pere de Cabrera s/n, 25001 Lleida, Spain
[b] Departament d'Enginyeria Mecànica, Universitat Rovira i Virgili, Av. Països Catalans 26, 43007 Tarragona, Spain
[c] Departament d'Informàtica i Enginyeria Industrial, INSPIRES Research Centre, Universitat de Lleida, Lleida, Spain

HIGHLIGHTS

- A novel PCM h-T function is implemented for PCM melting temperature optimization.
- Optimization is applied to find the optimum PCM melting in different climates.
- High energy savings are achieved in buildings with PCM-enhanced gypsum technology.
- In cooling dominant climates PCM melting at 26 °C achieves higher energy savings.
- In heating dominant climates PCM melting at 20 °C achieves higher energy savings.

ARTICLE INFO

Article history:
Received 18 February 2017
Received in revised form 8 May 2017
Accepted 13 May 2017

Keywords:
Passive cooling
GenOpt
Building energy simulation
PCM optimum melting

ABSTRACT

Globally, a considerable amount of energy is consumed by the building sector. The building envelope can highly influence the energy consumption in buildings. In this regard, innovative technologies such as thermal energy storage (TES) can help to boost the energy efficiency and to reduce the CO_2 emissions in this sector. The use of phase change materials (PCM), due to its high heat capacity, has been the centre of attention of many researchers. A considerable number of papers have been published on the application of PCM as passive system in building envelopes. Researches have shown that choosing the PCM melting temperature in different climate conditions is a key factor to improve the energy performance in buildings. In the present paper, a simulation-based optimization methodology will be presented by coupling EnergyPlus and GenOpt with an innovative enthalpy-temperature (h-T) function to define the optimum PCM peak melting temperature to enhance the cooling, heating, and the annual total heating and cooling energy performance of a residential building in various climate conditions based on Köppen-Geiger classification. Results show that in a cooling dominant climate the best PCM melting temperature to reduce the annual energy consumption is close to the maximum of 26 °C (melting range of 24–28 °C), whereas in heating dominant climates PCM with lower melting temperature of 20 °C (melting range of 18–22 °C) yields higher annual energy benefits. Moreover, it was found that the proper selection of PCM melting temperature in each climate zone can lead to notable energy savings for cooling energy consumption, heating energy consumption, and total annual energy consumption.

1. Introduction

The building envelope has a crucial impact on the energy conservation [1]. Globally, space heating and cooling account for over one-third of all energy consumed in buildings, increasing to as much as 50% in cold climate region [2]. Further on, a boom in the cooling energy demand is expected as a result of growing urbanization and wealth [3] which may lead to urban heat island (UHI) effects [4] and, on the other hand, the global warming due to climate change and its corresponding side effects such as extreme heatwave periods [5] are great influencing factors of this rapid temperature rise.

This goal could be approached by taking advantage of innovative technologies such as thermal energy storage (TES) [6]. The application of TES yields better system performance and reliability, better energy efficiency, economic benefits, thermal comfort for occupants, and less CO_2 emissions [7]. TES systems are classified

* Corresponding author.
E-mail address: lcabeza@diei.udl.cat (L.F. Cabeza).

http://dx.doi.org/10.1016/j.apenergy.2017.05.107

into three categories: thermochemical, sensible, and latent heat storage.

Thermochemical storage relies on thermochemical materials (TCM) undergoing either a physical reversible process involving two substances or reversible chemical reactions. In comparison to sensible and PCM, TCM has higher energy densities and lower volume of the storage material which results in more compact design. However, further research is required to apply this technology in buildings. Solé et al. [8] discussed the potential of TCM for building applications.

By the way, sensible heat is the simplest way of storing thermal energy by applying a temperature gradient to a solid or liquid media to store or release heat. Water has been used as the most common material for sensible heat storage. Additionally, for building applications other materials such as concrete, brick, and natural stones have been extensively used in building construction worldwide. However, for sensible heat storage in buildings massive materials are required which could be a drawback [9].

By the advent of technology and material design, today, latent heat storage is a popular means for passive design of buildings [10]. Latent heat storage depends on the material phase change enthalpy to accumulate heat within a small temperature range, providing greater energy density than that obtainable with sensible heat storage over the same temperature gradient. However, in some materials volumetric expansions may happen during the melting process [11]. Materials with a solid-liquid phase change, which are appropriate for heat or cold storage in building envelopes, are generally referred to as phase change material (PCM) [12]. The PCM technology due to its exclusive assets for thermal regulation of buildings has been the centre of attention of many researchers [13,14]. An important feature that differentiates the PCM from other typical thermal mass materials with sensible heat is the capability of storing high amounts of heat in small temperature range due to its high heat capacity. However, appropriate material selection is of a high importance to properly apply it into buildings. PCMs are classified into two main categories: organic and inorganic. Examples of the organic PCMs are paraffin, fatty acids and the polyethylene glycol. Advantages of organic PCMs are: negligible or non subcooling, chemical and thermal stability, and non-corrosiveness, and their disadvantages are: low phase change enthalpy, low thermal conductivity, and flammability. Examples of inorganic PCMs are salt hydrates [15] that have greater change enthalpy, however, they have some drawbacks such as: subcooling, corrosion, phase separation, phase segregation, and lack of thermal stability [12,16]. So that, according to all properties mentioned above, material selection should be based on the application requirements. For further information about the available PCMs for building applications one can refer to researches carried out by Cabeza et al. [17] and Barreneche et al. [18].

PCM can be incorporated into building construction materials by direct incorporation, immersion, shape-stabilized PCM, form-stable composite PCM and encapsulation which are categorized into macroencapsulation and microencapsulation [19,20]. Macroencapsulation means inclusion of PCM in a macroscopic containment (usually larger than 1 cm in diameter) such as tubes, pouches, spheres, panels or other containers. In microencapsulation, solid or liquid particles of 1–1000 μm are encapsulated in a thin, high molecular weight polymeric film. Then, the enclosed particles can be incorporated in any matrix that is adaptable with the encapsulating film and adoptable with both PCM and the matrix [12,17,19].

In most applications, PCMs are microencapsulated [17] to avoid the movement of liquid phase PCM and on the other hand to avoid its contact with the surrounding and not to adversely affect e.g. the construction material. The main advantages of microencapsulation of PCM are improvement of heat transfer to the surrounding due to large surface to volume ratio of the capsules and the enhancement of cycling stability since phase separation is limited to microscopic distances. Further on, the leakage and evaporation problems are solved in this method and the loss of PCM under construction work e.g. cutting the wallboard or screwing is negligible. In addition, they could be integrated into other materials to form composite materials [12].

PCMs can be incorporated into building construction materials in various ways to provide passive cooling benefits such as gypsum plasterboard with microencapsulated paraffin [21] which is a unique solution to enhance thermal capacity of lightweight buildings, plaster with microencapsulated paraffin [22] that could be applied on the surface of the walls, concrete with microencapsulated paraffin [23], shape-stabilized paraffin panels [24], PCM bricks [25] and wood with PCM [26]. Additionally, PCMs have vast applications for building components such as slabs [27], floors [28], blinds and windows [29,30].

In buildings the TES could be applied either as a passive [10] or as an active system [31]. Both of these approaches could be appropriate and their implementation depends on some factors such as product availability, cost, climatic conditions, and energy prices [32]. However, high levels of energy efficiency in building envelope elements could be attained by passive design approach as an integrated design by taking advantage of sun as a clean and renewable source of energy. In winter, PCM can be melted during the sunny hours and store the solar energy, and late on the stored heat could be released through its solidification process. Hence, PCM melting temperature should be low enough to be melted during winter sunny hours. On the other hand, in summer, PCM through its melting process prevents cooling peak load to the indoor environment. PCM is solidified during night time and hence charged for the following day. In this case, solidification temperature of PCM has to be high enough so the PCM can be charged by free cooling at night.

The application of passive PCM systems to improve the heating and cooling energy performance in buildings has been growing rapidly over the last two decades [33]. The passive PCM technology can be applied in different parts of a building as an integrated passive design. Baetens et al. [34] reviewed some possible applications of PCM technology integrated into buildings materials such as wallboards, concrete, and thermal insulation. However, using PCM-enhanced building envelopes for passive cooling has been popular among researchers [20,35].

As an example, an experimental and numerical study was carried out by Jamil et al. [36] to investigate the potential of PCM in decreasing the zone air temperature and enhancing occupant thermal comfort in a naturally ventilated house located in Melbourne, Australia. In their experimental study, PCM with melting temperature of 25 °C (melting range of 23–27 °C) was installed between ceiling insulation and plasterboard of a bedroom. Their results showed 34% reduction of thermal discomfort hours in the room with PCM inclusion. Afterwards, they performed numerical simulation to analyse the impact of occupants behaviour on the effectiveness of PCM technology. It was found that, if occupants appropriately open the windows at night time to let cool air in and during day maintain the internal doors closed, the thermal discomfort could be reduced by 52%.

The principal functionality of the PCM technology is to reduce the HVAC demand in mechanically ventilated buildings, or to moderate the indoor air temperature providing higher air quality for occupants by enhancing the thermal mass of the envelope [37]. The thermal behaviour of buildings is associated with complex physical phenomena and their performance is highly corresponded to the indoor and outdoor boundary conditions, especially, when the PCM is integrated into the building envelopes. For this reason, building simulation tools are invaluable and necessary to analyse and evaluate the energy performance and comfort conditions,