Energy and Buildings 158 (2018) 1097–1105

Contents lists available at ScienceDirect

Energy and Buildings

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

Thermal stress reduction in cool roof membranes using phase change materials (PCM)

Mohammad Saffari[a], Cristina Piselli[b], Alvaro de Gracia[c], Anna Laura Pisello[b,d], Franco Cotana[b,d], Luisa F. Cabeza[a,*]

[a] GREiA Research Group, Inspires Research Centre, University of Lleida, Pere de Cabrera s/n, 25001 Lleida, Spain
[b] CIRIAF – Interuniversity Research Centre, University of Perugia, Via G. Duranti 67, 06125 Perugia, Italy
[c] Departament d'Enginyeria Mecanica, Universitat Rovira i Virgili, Av. Paisos Catalans 26, 43007 Tarragona, Spain
[d] Department of Engineering, University of Perugia, Via G. Duranti 93, 06125 Perugia, Italy

ARTICLE INFO

Article history:
Received 24 August 2017
Received in revised form 20 October 2017
Accepted 21 October 2017

Keywords:
Cool roof
PCM
Optimization
Simulation
Thermal stress

ABSTRACT

A considerable amount of energy is used in the building sector for air conditioning purposes. Additionally, the building sector contributes to the urban heat island (UHI) phenomenon which causes temperature rise in urban areas. Cool roof is an emerging passive cooling technology that can contribute to reduce the cooling energy use in buildings and to mitigate the UHI effects in the urban area. Cool roofs and reflective coatings, despite of being effective in terms of reducing the cooling thermal loads in buildings and decrease the UHI, can suffer from extreme thermal stress which negatively influences their lifespan and performance. Thermal energy storage (TES) is a promising technology which can be applied together with cool roof technology to decrease the extreme thermal stress due to solar radiation as well as providing thermal inertia to the building. In this study, simulation-based optimization will be used to optimize the PCM melting temperature when integrated into a polyurethane-based cool roof membrane to reduce the thermal stress of the cool roof and also to improve the annual energy performance of the building. The optimization results showed that the application of PCM and cool roof technologies together can reduce the severe thermal stress of the cool roof membrane when the optimization objective is the annual thermal stress of the cool roof. On the other hand, when PCM melting temperature is optimized to reduce the annual energy needs, higher annual energy savings could be achieved with acceptable reductions in the cool roof membrane thermal stress.

1. Introduction

Global warming is a critical issue in the world which endangers the life on earth. Hazardous emissions such as CO_2 are the main motivators of this negative climatic phenomenon. The building sector is responsible for consuming roughly 32% of the global final energy use and emitting roughly one-third of all greenhouse gas emissions [1,2].

In Europe, buildings consume about 40% of energy, of which 50% of this comes from heating, ventilation, and air conditioning. For this reason, reduction of space air-conditioning requirements in buildings is of a high importance to ensure the energy efficiency in this sector [3–5].

Further on, a substantial rise in cooling energy demands is expected by 2050. The estimated growth in cooling demands is about 150% globally and about 300%–600% in developing countries [6]. Moreover, the building sector also contributes to the urban heat island (UHI) phenomenon in urban areas, in which elevated surface and air temperature could be felt in urban areas compared to outskirts [7]. Accordingly, a serious global effort towards energy efficiency in buildings is essential to decrease building energy demand growth while maintaining thermal comfort and improved quality of life for occupants both in indoor and outdoor environment.

Passive cooling techniques could be effective methods to improve the cooling energy performance in buildings [8,9] by moderating the temperature fluctuations in building zones, thus offering long-term energy efficiency and indoor thermal comfort [10,11].

Cool roof is an emerging passive cooling technology which can contribute to reduce cooling demand in buildings and UHI effects. Further on, it can improve the thermal comfort of occupants, reduce the HVAC size, decrease the roof surface temperature, and extend the life of the roofing system [12,13]. Cool roofs have exterior

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

https://doi.org/10.1016/j.enbuild.2017.10.068
0378-7788/

surfaces or coatings that reduce solar absorption and increase thermal emittance. They maintain lower surface temperatures and decrease heat flows into the building [14]. However, the high solar reflectance created by cool roofs may increase heating energy requirements and building energy use during heating seasons especially in heating dominant weather conditions [14].

Due to the importance of cool roofs for building energy efficiency enhancement, many important international building energy-efficiency standards such as ASHRAE 90.1, ASHRAE 90.2, the International Energy Conservation Code, and California's Title 24 have adopted cool-roof credits or requirements [15].

In addition, many authors have investigated and analyzed the potential benefits that cool roof technology can offer to increase the cooling energy performance in buildings, and to improve the urban microclimate [16] based on experiments or simulation techniques [17]. For example, Stavrakakis et al. [18] experimentally and numerically analyzed the influence of the cool roof technology in a school building in Greece under Mediterranean climate zone. They concluded that the application of a cool roof can achieve annual energy savings up to 7.4%, and cooling energy savings up to 50%, when heat pumps are used. In another study, Zinzi and Agnoli [19] numerically studied the effect of cool roofs on the energy performance of residential buildings in various Mediterranean cities using the DesignBuilder energy simulation software [20]. It was found that cool roofs could be considerably energy-efficient in the central and southern Mediterranean areas, particularly in insulated houses, where the increase of heating demand is limited. Further on, Gagliano et al. [33] investigated the thermal and environmental behavior of cool roofs, green roofs, and traditional roofs using numerical simulation. They found that both green and cool roofs can substantially contribute to energy saving and bring environmental benefits compared to highly-insulated typical roofs, which require thick insulation in comparison to cool roofs and green roofs to have better performance.

Cool roofs and reflective coatings, despite of being effective in terms of reducing the cooling thermal loads in buildings and decreasing the UHI, can suffer from extreme thermal stress which negatively affects their lifespan and workability [22]. In fact, aging and weathering can reduce the solar reflectance of cool roofing materials. High temperatures can accelerate damaging chemical reactions and degradation in materials, cause loss of volatile components, and soften some polymers. Temperature fluctuations caused by solar radiation and weather conditions, either gradual or sudden can create thermal stress due to differential thermal expansion [21].

By the advent of technology and advancement in material science, new doors have been opened towards innovative design in the field of building science and renewable energies to achieve further energy efficiency in these sectors. Thermal energy storage (TES) is a promising technology that can enhance the energy efficiency in the building and industry sectors [23]. Particularly, TES is a technology which can lead to a low-carbon future by reducing the energy use in buildings due to their high thermal capacity and their capability to create a balance between diurnal and nocturnal energy demand [24]. TES materials can store a high amount of energy in terms of sensible heat and latent heat. Materials used for latent heat storage are known as phase change materials (PCM) [25–30]. PCMs are distinguished because of their high latent heat capacity which allows them to accumulate a high amount of energy in small temperature intervals resulting in a considerable increase in the thermal mass of building components or the building envelope when incorporated in it [31–33].

Cool roof by itself is an innovative technology; however, when applied together with PCM can overcome some of its weaknesses, specifically, heat stress due to solar radiation and ambient temperature. So far, however, there has been little discussion about durability enhancement of a cool roof membrane using PCM in the literature.

As an example, in a recent study, Pisello et al. [22] developed a new composite material made of a polyurethane liquid water resistant cool membrane enhanced with non-encapsulated PCM melting at 25 °C and with 148 kJ/kg heating of fusion, acting as shape stabilized thermal buffer additive. Afterwards, they experimentally analyzed the influence of TES on decreasing the thermal fluctuations of the polyurethane cool roof membrane under solar radiation hitting building roof surfaces. Their results showed that inclusion of PCM could improve the spectral reflectance in the near infrared region of the solar spectrum up to 10%, and could maintain the required flexibility of the membrane together with its superficial finishing characteristics.

In another study, Roman et al. [34] compared the application of a cool roof and PCM in terms of UHI reduction and minimizing the heat flux entering from roof surfaces into the building. Their simulation results showed that the cool roof technology can effectively reduce the UHI, where the PCM technology can considerably reduce heat fluxes entering from roof surface into the building. In addition, they added that the combination of an asphalt roof with a PCM layer can be an effective solution to scale down UHI effects.

Similarly, a simulation-based study carried out by Pisello et al. [35] compared four different roofing technologies with regards to their cooling energy benefits. Their solutions included roof covered with a bitumen sheet membrane, a roof covered with a cool membrane, a PCM-integrated cool roof membrane, and a PCM-integrated bitumen membrane. It was concluded that a PCM-integrated cool roof membrane can reduce the cooling energy use by about 11%, whilst a PCM-integrated bitumen membrane can decrease the cooling needs up to 12.6% compared to the prototype with only bitumen membrane.

The literature review carried out shows that combining cool roof and PCM innovative technologies can offer substantial cooling energy savings, and further on, can enhance the performance of the cool roof membrane. Actually, a trade-off between these two technologies can bring benefits from both the cool roof technology and PCM technology. In fact, the cool roof technology reduces solar heat gains into the building through their highly reflexive surfaces and accordingly decrease UHI phenomenon, and on the other hand, the PCM technology can store a high amount of heat coming from roof surface and more importantly moderate the temperature fluctuations in the cool roof membrane.

However, to the best authors knowledge, no report has been found so far using numerical simulation and optimization to find out the optimum PCM melting temperature to reduce cool roof membrane heat stress, and to improve the overall energy performance of the building. Actually, an important question that needs to be asked, however, is how the application of the cool roof together with PCM can influence the HVAC requirements in a building.

Thus, in the present study, simulation-based optimization will be used to optimize the PCM melting temperature when implemented together with polyurethane-based cool roof membrane, on one hand, to decrease the deteriorating heat stress on the cool roof membrane, and on the other hand, to reduce the annual HVAC energy use under different warm temperature climate regions.

2. Methodology

2.1. Reference building prototype

To implement the new cool roof and PCM passive strategies, a multi-family residential apartment was selected from ASHRAE Standard 90.1–2013 prototype building models and slightly modified [36]. The ASHRAE Standard 90.1 prototype building models were developed by the Pacific Northwest National Laboratory in