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Coupling of solar reflective cool roofing solutions with sub-surface phase change materials (PCM) to avoid condensation and biological growth

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Abstract

Cool roofs are effective solutions to counter the overheating of building roofs, inhabited spaces below and urban areas in which buildings are located thanks to their capability of reflecting solar radiation. Nonetheless, the relatively low surface temperatures that they induce can cause condensation of humidity and leave the surface wetted for large part of the day, thus promoting the growth of bacteria, algae and other biological fouling; this can cause a quick decay of the solar reflective performance. Biological growth is countered by surface treatments, which, however, may be toxic and forbidden in many countries and may also vanish quickly. It can also be countered by lowering the thermal emittance and thus decreasing heat transfer by infrared radiation to the sky and the consequent night undercooling, but this can decrease the performance of cool roofs. An alternative approach, which is analyzed in this work, is to embed in the first layer below the cool roof surface a phase change material (PCM) that absorbs heat during the daytime and then releases it in the nighttime. This can increase the minimum surface temperatures, thus reducing the occurrence humidity condensation and also the biological growth. In this work, preliminary results on the coupling of a cool roof surface with a PCM sublayer are presented, being obtained by theoretical investigation on commercial materials and taking into account the time evolution pattern of the environmental conditions.

Keywords: cool roof; phase change material; PCM; condensation; biofouling.

1. Introduction

1.1. Cool roofs and their aging

Cool roofs are roofing solutions reflective of solar radiation thanks to their high solar reflectance, or albedo. They can prevent overheating of both individual buildings and entire urban areas. Their potential has been quantitatively investigated in the USA since the eighties of the last century (Taha et al, 1989), in response to both the urban heat island (UHI) effect and the need of reducing electric energy and peak power absoprtion for air conditioning. Many studies have followed, for example, evidencing the effectiveness of gradually increasing the albedo of a city by choosing high-albedo surfaces to replace darker materials during routine maintenance of roofs, as well as the usefulness of establishing sponsored incentive programs, product labeling, and standards to promote the use of high-albedo materials for buildings (Rosenfeld et al, 1995). Surveys on cool roofing materials were made (Berdahl & Bretz, 1997), strong savings of cooling energy and peak power were shown (Akbari et al, 1997, 1999), and the researchers also started to pay attention to the long-term performance of high-albedo roof coatings (Akbari & Bretz, 1997). Steps were then taken by cities in the warm half of USA towards the incorporation of cool roofs in the revised

ASHRAE building standards and the inclusion of cool surfaces as tradeable smog-offset credits in Los Angeles (Rosenfeld et al, 1998), eventually culminating in prescriptive requirements, such as the inclusion of cool roofs in energy codes like Title 24 of California Code of Regulation (Levinson et al, 2005).

From the USA, cool roof technologies have spread worldwide. Among the others, studies evidencing their potentialities were made in Europe (Synnefa et al, 2006; 2007; Zinzi, 2010) and the Cool Roofs Project was co-funded by the European Union to promote high-albedo surface as a UHI mitigation strategy and a measure for reducing cooling loads (Synnefa & Santamouris, 2012). Moreover, a hot theme in both Europe and the USA is the contribution to offset CO_2 production that can be achieved by increasing the albedo of urban surfaces (Akbari et al, 2009). The usefulness of cool roofs was also investigated with regard to cold climates, such as Montreal (Touchaei & Akbari, 2013). In this regard, while cool roofs have shown to significantly reduce the contribution to the UHI in the hot season, the penalization introduced in regions with cold winter seems often negligible in terms of either energy needs for heating or lower heat released to, and thus warming, the outer urban environment (Magli et al, 2016).

Nomenclature

c	specific heat (J/(kg°C))
c_l	specific heat of the liquid/high temperature phase (J/(kg°C))
c_s	specific heat of the solid/low temperature phase (J/(kg°C))
d_l	mass density of the liquid/high temperature phase (kg/m^3)
d_s	mass density of the solid/low temperature phase (kg/m^3)
h_{ce}	external convective heat transfer coefficient (W/(m^2°C))
h_{ci}	internal convective heat transfer coefficient (W/(m^2°C))
h_{re}	external radiative heat transfer coefficient (W/(m^2°C))
h_{ri}	internal radiative heat transfer coefficient (W/(m^2°C))
I_{sol}	solar irradiance (W/m^2)
k	thermal conductivity (W/(m°C))
k_l	thermal conductivity of the liquid/high temperature phase (W/(m°C))
k_s	thermal conductivity of the solid/low temperature phase (W/(m°C))
L	total thickness (m)
q_{sl}	latent heat (J/kg)
T	temperature (°C)
T_{air}	ambient air temperature (°C)
T_{air}	ambient air temperature (°C)
T_{dp}	dewpoint temperature (°C)
T_e	external effective temperature (°C)
T_i	internal temperature (°C)
T_{me}	mean absolute external temperature (K)
T_{se}	external surface temperature (°C)
T_{sky}	sky temperature (°C)
T_{sl}	phase change temperature
$T_{sol/air}$	sol-air temperature (°C)
t	time (s or day)
v_{wind}	wind velocity (m/s)
x	coordinate across thickness (m)
Δq_i	change of the entering heat flow rate per unit surface (W/m^2)
ΔT_{sl}	half amplitude of the phase change interval (°C)
ε_{ter}	(external) thermal emittance ($0<\varepsilon_{ter}<1$)
ρ_{sol}	(external) solar reflectance ($0<\rho_{sol}<1$)
σ_0	Stefan-Boltzmann constant ($5.67\cdot10^{-8}$ W/(m^{2}K^4))

Cool roofs can in fact be seen as the technological rediscovery of ancient concepts: in the Mediterranean areas, roofs and walls of buildings are white since thousands of years. On the other hand, today we know that a white or very light color is not an objective term of evaluation but just a qualitative indicator, so current cool roof technologies are based on measurement of materials performance and calculation of resulting benefits. More specifically, we know that a cool roof must have high solar reflectance, *i.e.* the ratio of reflected and incoming solar radiation; it should also have high thermal (or infrared) emittance, *i.e.* the ratio of radiation emission in the thermal (or far) infrared and maximum theoretical emission at the same surface temperature. Both solar reflectance and thermal emittance are measured as a percentage, or a fraction of the unit. The higher solar reflectance is, the lower the fraction of solar radiation that is absorbed by a surface is. Such an absorbed radiation can then be returned to the atmosphere by convection with the air and by thermal radiation to the sky. With still air, as in the absence of wind, heat removal mainly occurs by thermal radiation, provided that the thermal emittance is high. In contrast, low solar reflectance and/or low thermal emittance may cause the surface to overheat and, consequently, heat to be transmitted to the roof structure and the living spaces below. This contributes to building overheating and to the correlated UHI effect either directly, in terms of heat transfer to the external air by convection, or indirectly, due to the removal of the transmitted heat from the living spaces by means of the air conditioning systems. The latter contribution is augmented by the compressor power absorption, which increases with the external air temperature.

Two different families of cool roofing solutions can be identified: cool white technologies for flat roof coverings, such as the example in Figure 1, by far the ones more commonly used, and cool color technologies for sloped roofs, designed to show a reflection spectrum in the visible range (0.4-0.7 μm) as needed to obtain a desired color, but at the same time high capacity of reflection in the near infrared (NIR, 0.7-2.5 μm), where solar radiation falls by more than 50% but is invisible to the human eye.

Figure 1. Flat roof with cool white waterproofing membrane
(Tecnopolo building of the University of Modena and Reggio Emilia, Modena, Italy).

Cool white roofing solutions can be of many types: field applied coatings (paints, fluid applied membranes, etc.), reinforced bitumen sheets made of modified bitumen (elastomeric or plastomeric), single-ply sheets and membranes (thermoset or thermoplastic), tiles (ceramic, concrete, etc.), asphalt or bituminous shingles, pre-painted metal roofs, built-up roofing. They can show initial solar reflectance as high as 80-85%, and thermal emittance usually in the range from 80% to 95% for non-metallic materials (CRRC, 2015; US EPA, 2015; ECRC, 2015). On the other hand, it is very difficult to retain the initial reflectance value due to chemical and physical deterioration of materials and, above all, to soiling caused by pollutant deposition and biological growth (Berdahl et al., 2002, 2008; Ichinose et al., 2009; Sleiman et al. 2011 ; Paolini et al. 2014).

In this regard, reflectance and emittance of opaque building elements are those of the most superficial matters, that is of a surface layer or a coating with thickness as low as a few tenths of millimeters, and both properties are generally unaffected by the underlying substrate, whatever this is. Therefore, being the reflectance that of the most superficial matter, a superposed layer of atmospheric suspensions and/or grown up organic matter may strongly affect the reflective performance. Both initial and aged values of solar reflectance are thus provided in the framework of the CRRC rating program, obtained by natural exposure in three locations with different climate for at least three years (Sleiman et al, 2011). The development of matrices and white pigments chemically and physically stable permits to avoid degradation of the reflectance, such as that associated to yellowing of the surface, whereas several approaches are exploited to reduce soiling, such as controlling the surface porosity and roughness, possibly applying super-hydrophilic or super-hydrophobic surface treatments, or self-cleaning coatings based on photo-catalysis (Diamanti et al, 2013). A few approaches, mentioned in the following section, are also available to limit biological growth.

1.2. Biological growth and deterioration of building surfaces

As anticipated above, the deterioration of cool roofs and, more generally, of external building surfaces is due to several causes: aging and weathering, soiling and deposition of atmospheric black carbon, dust, and organic and inorganic particulate matter, as well as microbiological growth (Sleiman et al, 2014; Mastrapostoli et al. 2016). It is often difficult to distinguish between non biological and biologically-mediated weathering of materials: the two processes can occur concurrently, each one contributing to the overall deleterious effects (Gaylarde & Morton, 2002). The development of microbial communities on wetted surfaces is called biofilm, and it becomes gradually a more complex system (Characklis & Marshall 1990). Biofilms on building surfaces can contain cyanobacteria, heterotrophic bacteria, algae, fungi, lichens, protozoa, and a variety of small animals (arthropods) and plants (briophyte) (Gaylarde & Gaylarde, 2005). Biological growth is influenced by both external conditions and intrinsic characteristics of the building material (Tomaselli et al., 2000). External conditions are represented by rainfall, wind, sunlight, temperature and humidity as these determinate the water availability, an essential element to the microbial metabolism: wet surfaces promote autotrophic organism growth, therefore a higher susceptibility to biofouling occurs in rainy regions, as well as in the heavy rain season (Tran et al., 2014). The issue arises also in humid climates due to the low surface temperatures of cool roofs and persistent condensation of atmospheric moisture. On the other hand, high temperatures induce water evaporation by heating the materials, and wind is also important for the drying phenomenon. Altogether the climatic conditions determine, depending on the geography position, the moisture and light conditions that define the micro-climate on building surfaces, which is the major environmental factor influencing biological growth (Ariño et al., 1997): if moisture is high enough, and lighting and temperature conditions are suitable, colonization of the surface of new buildings can occur very quickly (Wee & Lee, 1980). Also the building design and the orientation of the building surface influence external factors of bio growth: the north-facing facades, which are wetter and less sunny, get colonized faster (Ariño et al., 1997). More details on biological growth are given in (Ferrari et al, 2015).

In order to limit biological growth, surface treatments based on biocides can be used, but their effects may however vanish quickly; moreover, they may be toxic and forbidden in many countries. Biological growth can also be countered by lowering the thermal emittance and thus decreasing heat transfer by infrared radiation to the sky and the consequent night undercooling, but this can also decrease the performance of cool roofs. The alternative approach to counter biological growth on cool roofs and similar building surfaces that is analyzed here is to embed in the first layer below the cool roof surface a phase change material that absorbs heat during the daytime and then releases it in the nighttime. This can increase the minimum surface temperatures, thus reducing humidity condensation and, with this, biological growth. In this work, preliminary results on the coupling of cool roofs and PCMs are presented, obtained by theoretical investigation on commercial materials and taking into account the time evolution pattern of the environmental conditions in a sub-Mediterranean climate with low wind and relatively high humidity.

1.3. Phase change materials and their coupling with cool roof surfaces

Latent heat storage technologies that use phase change materials (PCM) embedded in lightweight building elements are considered as an interesting alternative to sensible storage by heavy weight constructions (Zalba et al., 2003; Khudhair & Farid, 2004; Mavrigiannaki & Ampatzi, 2016): these materials can undergo a phase change, typically melting/solidification, and therefore exchange more heat with the environment in terms of latent heat rather than through solely their sensible heat storage capacity. In recent times the attention has also been drawn by coupling of PCMs with cool roofs, studied by either numerical simulation or experiments. Experimental results (Karlessi et al., 2011) demonstrated that PCM incorporated in building coatings yields lower surface temperatures than either common coatings or cool infrared-reflective coatings. The numerical investigation by (Aguilar et al., 2013) extended previous work by considering the impact of PCM embedded in roofing module on cooling energy and showed that solar reflectance is the parameter with the biggest impact, but PCMs may be worthwhile in locations where the reflectance may undergo a sharp decrease due to soiling; moreover, they verified that simulation is a powerful tool for the involved multi-parameter analyses. Roman et al., 2016 showed through simulation that a PCM allows a sharp decrease of the maximum through-roof heat gain at a wide range of albedo. In (Chou et al., 2013) the coupling of a metal sheet cool roofing structure with a PCM was studied in order to absorb the downward heat flow induced by incident solar radiation and then release it back to the environment by convection during the nocturnal cycle; experimental and numerical analyses showed that the downward thermal flow through the roof into the house can be significantly reduced. The study of (Pisello et al., 2016) was aimed at the development and prototyping of a cool polyurethane-based membrane with PCM inclusion for roofing applications, whose relevant thermophysical properties were assessed by laboratory analyses. In (Chung & Park, 2016) a PCM cool roof system was created using PCM doped tiles; experimental results showed that such tiles, in summer weather conditions, allow a decrease of surface temperature while keeping low the temperature in the room below.

Generally speaking, most of the studies have shown that PCM can smooth both positive and negative peaks of surface temperature and thus improve thermal comfort and reduce cooling energy demand, but none seems to have yet paid attention to the specific issue of using PCM to limit condensation and biological growth on cool roof surfaces. This is therefore the topic of investigation in this work.

2. Model and case study

In order to parametrically investigate the thermal behaviour of a cool roof coating coupled with a PCM, a one-dimensional mathematical model of the roof system was implemented in the Matlab programming environment. The model, based on a finite-volume approach with implicit discretization of the time derivatives, takes into account the cyclical variability of the boundary conditions (temperature, solar irradiance, heat transfer coefficients) and the temperature dependence on the thermophysical properties of materials. It has been used to identify the time periods during which the external surface temperature falls below the dew-point and the risk of humidity condensation occurs. In this way, a comparison of the situation with and without a PCM layer below the cool roof surface has been carried out, considering also the case of surfaces with relatively low thermal emittance.

A flat roof was considered in this study. Hourly weather data on air temperature, sky temperature, wind velocity, solar irradiance, and dew-point temperature were obtained over the whole year from the TRNSYS programming environment (TMY data). Representative time evolution patterns are shown in Figure 2.

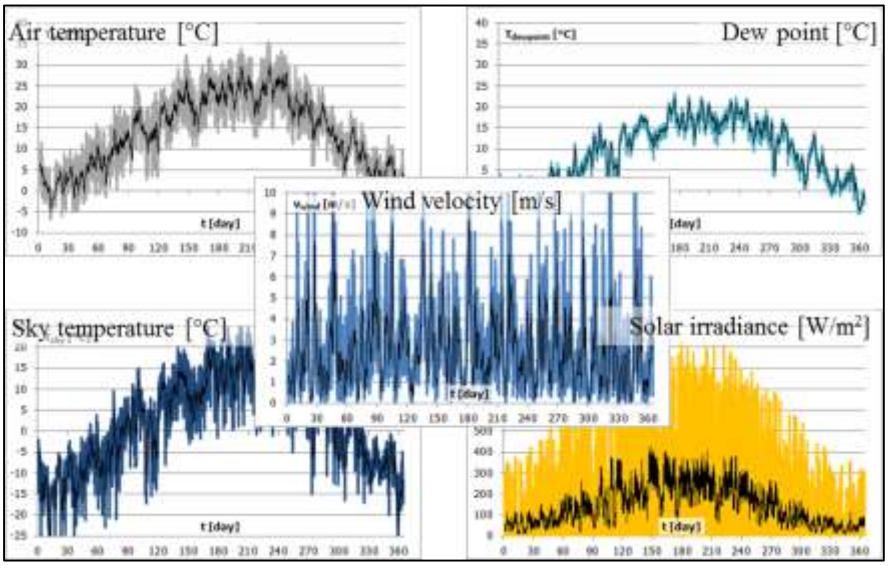


Figure 2. Ambient conditions over the year for Bologna, Italy
(data from TRNSYS, the black lines represent the daily average).

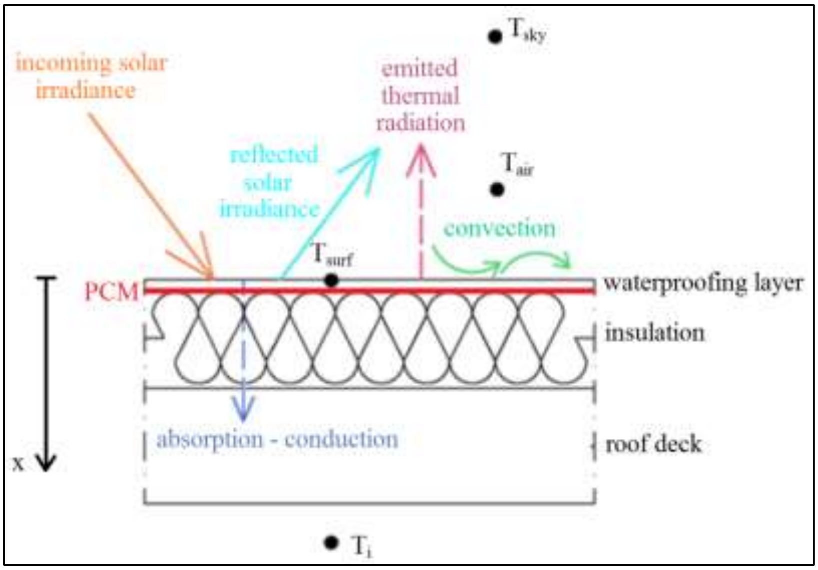


Figure 3. Roof structure and surface heat transfer processes.

The heat transfer process is depicted in Figure 3. More specifically, the boundary condition at the external surface of the solid matter (x=0), delimiting the external environment from the waterproofing layer, is expressed as

$$(h_{ce} + h_{re})\left[T_{sol/air}(t) - T(t)\big|_{x=0}\right] = -k\left.\frac{dT(t)}{dx}\right|_{x=0} \tag{1}$$

where the so-called sol-air temperature $T_{sol/air}$ (°C) is calculated as follows: from the effective external temperature T_e (°C) and the absorbed fraction of the solar irradiance I_{sol} (W/m^2) that results from the surface solar reflectance ρ_{sol} ($0<\rho_{sol}<1$):

$$T_{sol/air}(t) = T_e(t) + \frac{(1-\rho_{sol})I_{sol}(t)}{h_{ce} + h_{re}} \tag{2}$$

The effective external temperature T_e (°C) is in turn the average of air and sky temperatures, T_{air} and T_{sky} (°C), weighted by the external convective and radiative heat transfer coefficients, h_{ce} and h_{re} (W/(m^2°C)):

$$T_e(t) = \frac{h_{ce} T_{air}(t) + h_{re} T_{sky}(t)}{h_{ce} + h_{re}} \tag{3}$$

Air temperature and sky temperature, as well as the solar irradiance and, consequently, T_e and $T_{sol/air}$, are function of the time t (s). The convective heat transfer coefficient h_{ce} is evaluated from the wind velocity v_{wind} (m/s) according to ISO 6946 (ISO, 2007a):

$$h_{ce}(t) = 4 + 4v_{wind}(t) \tag{4}$$

The radiative heat transfer coefficient h_{re} is again evaluated according to ISO 6946 at the mean absolute external temperature T_{me} (K), also considering the thermal emittance ε_{ter} ($0<\varepsilon_{ter}<1$), as

$$h_{re} = \varepsilon_{ter} 4\sigma_0 T_{me}^3(t) \tag{5}$$

where σ_0 is the Stefan-Boltzmann constant ($\sigma_0=5.67\cdot10^{-8}$ W/(m^{2}K^4)), and

$$T_{me}(t) = \frac{1}{2}\left[T_{sky}(t) + T(t)\big|_{x=0}\right] \tag{6}$$

An explicit approach is generally followed to evaluate the radiative heat transfer coefficient from the calculated surface temperature.

Concerning thermal interaction between the roof structure and the inhabited space below, the indoor temperature T_i (°C) was assumed to be controlled by an appropriate air conditioning system and kept constant at a level adequate to thermal comfort, *e.g.* T_i=27°C for the summer period in the analyses presented here. The boundary condition at the internal surface (x=L), delimiting the roof structure from the indoor space, is expressed as

$$(h_{ci} + h_{ri})\left[T(t)\big|_{x=L} - T_i\right] = k\frac{dT(t)}{dx}\bigg|_{x=L} \tag{7}$$

Constant values obtained from ISO 6946 were used for both the internal convective coefficient h_{ci}, taken equal to 0.7 W/(m^2°C), and the internal radiative coefficient h_{ri}, evaluated equal to 5.5 W/(m^2°C) by a formula analogous to eq. (5) for the typical value of the thermal emittance of inner building surfaces, equal to 0.9, and an internal absolute mean temperature of 27°C = 300 K.

The same model used in a previous work (Barozzi et al., 2009) was exploited for the heat transfer in the solid matter comprised between the external surface (x=0) and the internal one (x=L), including the PCM layer. In fact, the thermal behaviour of a PCM can be mathematically modelled through different approaches. The one adopted here is based on the definition of a fictitious equivalent material, whose specific heat c (J/(kg·°C)) is a function of temperature. Heat absorbed or released by such a fictitious material must be equal to that absorbed or released by the actual material for the same rise or decrease of temperature. This seems consistent with the literature (Zalba et al., 2003; Farid et al., 2004; Schossig et al., 2005; Carbonari et al. 2006; Tyage & Buddhi, 2007), which shows that currently available PCM do not change phase at a precise temperature level, but rather over a more or less narrow temperature interval. Moreover, the slope of heat absorption or release in the phase change interval is often similar to a gaussian distribution about the central temperature. In the industrial practice, either the central value or the amplitude of the phase change interval are modulated through an appropriate formulation of the PCM (for example, the phase change temperature of paraffin depends on the length of the molecular chains, which can be modulated in terms of statistical distribution about an assigned average value in order to obtain the desired properties).

Entering into details, the equivalent specific heat c of a PCM with latent heat q_{sl} (J/kg), specific heat c_s (J/(kg·°C)) of the solid phase (or the low temperature phase in solid-solid transitions) and specific heat c_l (J/(kg·°C)) of the liquid phase (or the high temperature phase) is represented in this study by a gaussian distribution in a range with amplitude $2\cdot\Delta T_{sl}$ about the nominal phase change temperature T_{sl} (°C) (see Fig. 3). This is described by the following relationship:

$$c(T) = c_s + (c_l - c_s)\cdot\left(\frac{T - T_{sl}}{2\Delta T_{sl}} + \frac{1}{2}\right) + \frac{q_{sl}}{\Delta T_{sl}}\cdot\frac{2}{\sqrt{\pi}}\cdot\exp\left[-\left(\frac{T - T_{sl}}{\Delta T_{sl}/2}\right)^2\right] \quad (8)$$

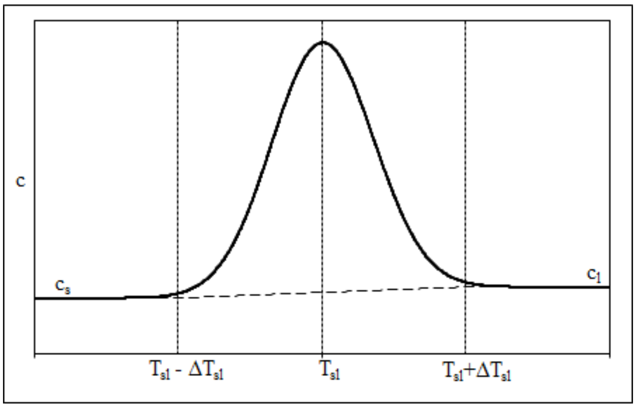


Figure 3. Effective specific heat of the PCM.

The thermal conductivity k (W/(m°C)) and other thermophysical properties which may vary significantly during the phase transition can also be modelled by assuming, over the phase change temperature interval, a linear variation between the values for the solid and the liquid phases, e,g. k_s and k_l (W/(m·°C)):

$$k(T) = k_s + (k_l - k_s)\cdot\left(\frac{T - T_{sl}}{2\cdot\Delta T_{sl}} + \frac{1}{2}\right) \quad (9)$$

Nonetheless, for the time being, certainly reliable data on the PCM are missing, so the properties of the solid and liquid phases are assumed to be equal for sake of simplicity, in view of their relatively low differences.

Table 1. Properties of the reference roof structure – Raw data from (ISO, 2007b).

Layer	Th. conductivity k (W/(m°C))	Mass density d (kg/m^3)	Specific heat c (J/(kg°C))	Thickness s (m)
Waterproofing	1.00	1200	1500	0.005
PCM	See Tab. 2			0 – 0.010
Thermal insulation	0.04	30	1400	0.100
Concrete	1.80	2400	1000	0.200

Table 2. Properties of the PCM panel – Raw data from (Le Du et al., 2012; DuPont, 2016).

Latent heat q_{sl}	70 kJ/kg
Phase change temperature T_{sl}	24.5°C
Half-amplitude of the phase change interval ΔT_{sl}	9.5°C
Specific heat $c_s \cong c_l$	2.3 kJ/(kg°C)
Thermal conductivity $k_s \cong k_l$	0.16 W/(m°C)
Mass density $d_s \cong d_l$	1001 kg/m^3

The properties of common building materials as reported in ISO 13786 (ISO, 2007b) for a thick concrete structure with thermal insulation were used for the different layers (see Tab. 1), whereas a commercial PCM board, DuPont Energain (DuPont, 2016), was considered for the PCM, to be introduced between the waterproof coating and the thermal insulation layer below with a thickness up to 10 mm. More specifically, a product developed by DuPont and called Energain® was considered, that is a composite PCM wallboard constituted of 60% of microencapsulated paraffin included in a polymeric structure; such a mixture is laminated by aluminium. Since the literature raises doubts on the material specifications (DuPont, 2016), these were integrated with experimental data from a third party (Le Du et al., 2012) (see Tab. 2).

3. Results

The model has been used to identify the time periods during which the external surface temperature T_{se} (°C) falls below the dewpoint T_{dp} (°C), and the risk of humidity condensation thus occurs. The process is depicted in Figure 4, where the surface temperature is plotted for a short mid-summer period, in case of absence of PCM and presence of a PCM layer with 10 mm thickness.

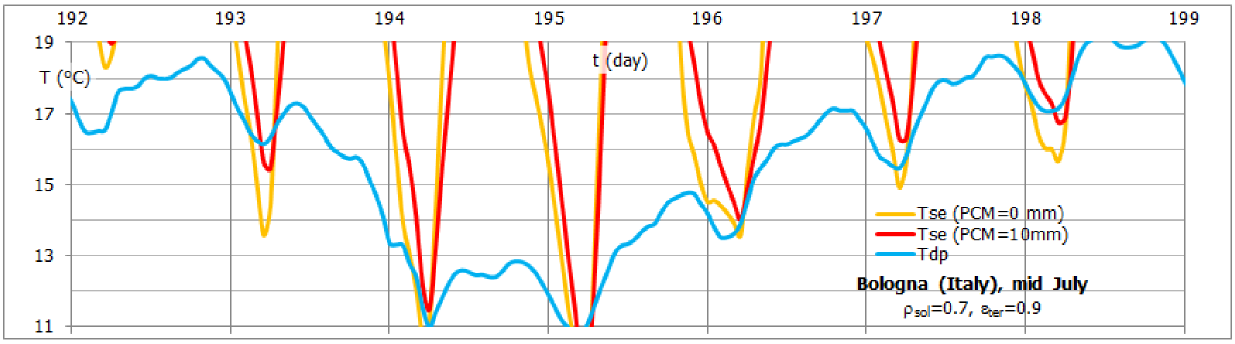
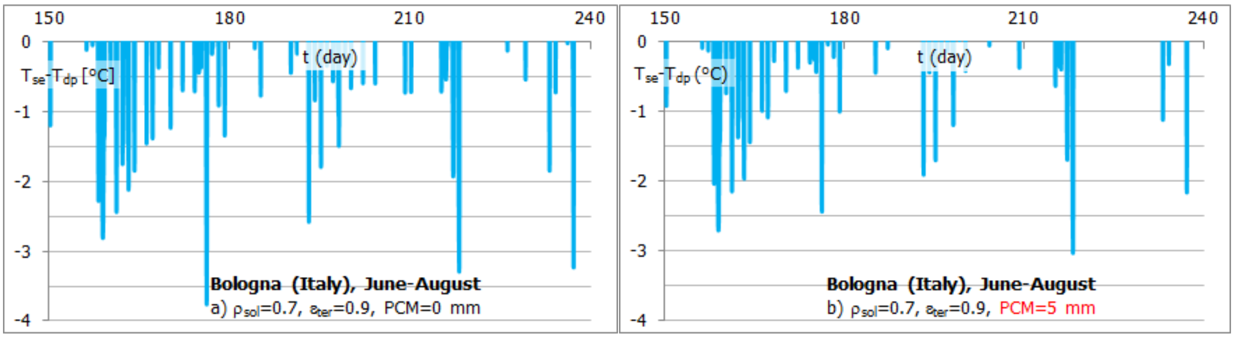


Figure 4. Time evolution patterns of dewpoint an surface (with and without PCM) temperatures: the risk of condensation exists where the surface temperature falls below the dewpoint temperature.

The frequency of the risk of condensation is represented in Figure 5-a) for a cool roof with thermal insulation but without PCM below the surface. It is then shown in Figure 5-b) and Figure 5-c), respectively, that the risk becomes lower with a 5 mm PCM layer, and much lower with a 10 mm PCM layer. In Figure 5-d) the risk of condensation is represented for a cool roof with thermal insulation and without PCM, but with thermal emittance 0.6 instead of 0.9; in this case one can observe that the reduced thermal emittance limits heat loss toward the sky during the nightime and, consequently, yields a risk of condensation similar to that provided by a 10 mm thick layer of PCM. Nevertheless, it was also found that an always positive change Δq_i (W/m^2) of the heat flow entering the inhabited space is obtained with respect to a cool roof surface with typical emittance of 0.9, that is an increased entering heat flow (see Fig. 6), whereas a cool roof surface with emittance 0.9 coupled with PCM causes an oscillating change Δq_i of the entering heat flow but with null average.



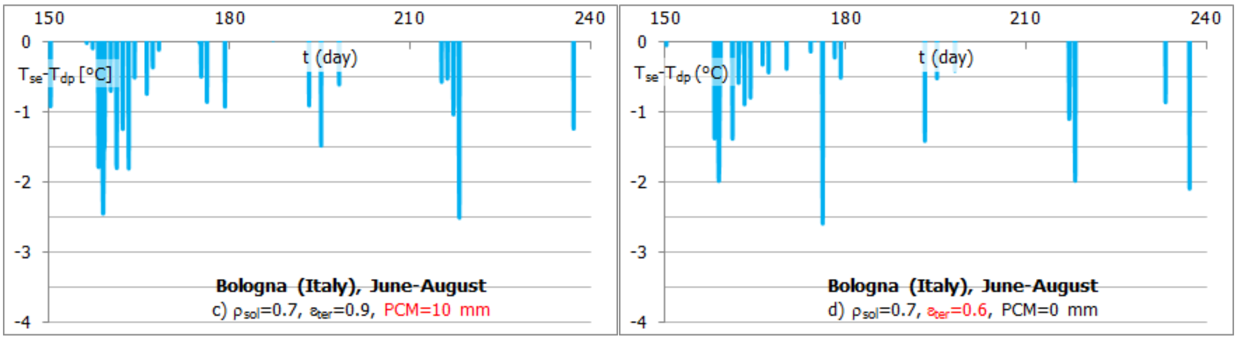


Figure 5. Risk of condensation for a) a typical cool roof, b) a cool roof coupled with 5 mm PCM, c) a cool roof coupled with 10 mm PCM, d) a cool roof with thermal emittance lower than usual.

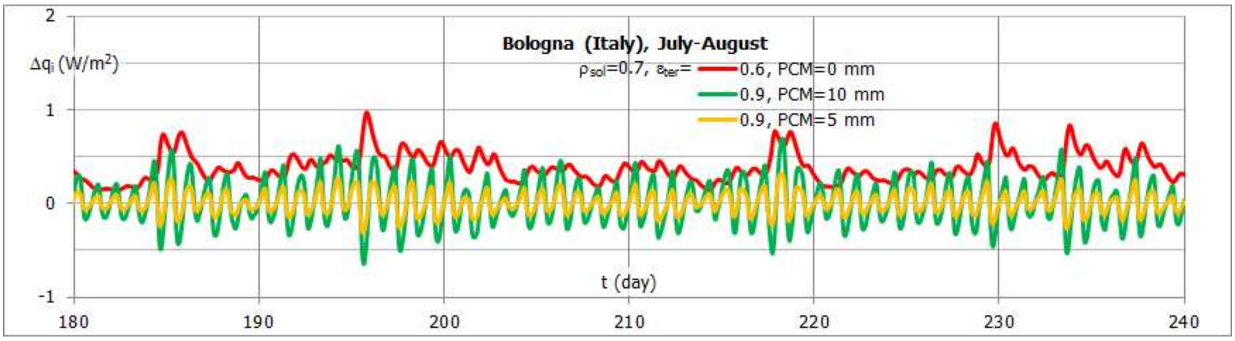


Figure 6. Change of the heat flow entering the inhabited space with respect to a typical cool roof with ρ_{sol}=0.7, ε_{ter}=0.9.

4. Concluding remarks

In this work, it was shown that a PCM can actually increase the nighttime surface temperature of a thermally-insulated cool roof, without affecting the overall performance of the cool roofing product. Heat is accumulated in the daytime by the PCM and then released in the nightime, increasing the minumum temperature and thus reducing the risk of falling below the dewpoint temperature, with the start of humidity condensation. Limiting humidity condensation my help preserve the cool roof surface from biological growth, especially for insulated roofs. A similar result can also be provided by a decrease of the thermal emittance at the external surface, but with a penalization of the cool roof performance in terms of heat transmitted to the inhabited space below and also maximim surface temperatures.

A relatively high mass fraction of PCM must be installed in the outer layer, either integrated in a waterproofing membrane or, as a board, placed just below the membrane, or below an outer metal sheet in insulated sandwich components. Effective results were in fact found only for a PCM board with thickness 10 mm and percent content of PCM around 60%. A lower amount of dispersed PCM may lead to an ineffective contribution.

In upcoming work, ambient data for different climatic conditions will be taken into account, considering either arid or very humid climates. Moreover, the analysis will focus on the choice of the phase change temperature, which must be slightly higher than the expected dewpoint temperature and should probably be optimized depending on the location. A more detailed model of the PCM is also under development, to be supported by experiments. Eventually, integration of the proposed solution in comprehensive dynamic models is a long-term objective.

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