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Thermal-energy analysis of roof cool clay tiles for application in historic buildings and cities

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ABSTRACT

More than 90% of historic buildings have traditional clay tiles as roof covering exposed to solar radiation, largely impacting buildings' thermal-energy performance and urban climate, since most of historic buildings are located in dense urban contexts. In this view, the optimization of these traditional elements could represent a key research issue, with the purpose of building energy retrofit and the constraint to preserve architectural heritage. This paper concerns the year-round analysis of the thermal-energy performance of a typical 16^{th} century historic residential building located in central Italy where an innovative cool clay tile is installed in a continuously monitored two-floor residential unit. Main results show that the proposed tiles, having good visual similarity with respect to the classic tiles, represent an effective solution to improve building energy efficiency during the cooling season and, if applied at larger scale, they could represent an effective UHI mitigation technique. In particular, maximum primary energy saving for cooling is 51%, while heating energy penalty is lower than 2%. The combined multi-scale analysis finally showed how these tiles represent an effective non-invasive strategy to (i) optimize thermal-energy performance of historic buildings even in temperate climate, and to (ii) mitigate urban climate.

Nomenclature

Abbreviations

T_{op}	operative temperature (°C)
T_{air}	indoor air temperature (°C)
T_m	mean radiant temperature (°C)
$Q_{heating}$	energy requirement for heating (kW h)
$Q_{cooling}$	energy requirement for cooling (kW h)

1. Introduction

Dense and highly populated urban environment, typical of city centers around the world (Salata, De Lieto Vollaro, De Lieto Vollaro, & Mancieri, 2014), are responsible for specific "urban microclimate" phenomena such as urban heat island (Borbora & Das, 2014). Such phenomena impact both human attitudes and health conditions, produce non-negligible increase of buildings energy need for cooling and CO_{2eq} gases emissions (Tsilini, Papantoniou, Kolokotsa, & Maria, 2015; Coma, Pérez, Castell, Solé, & Cabeza, 2014). An acknowledged methodology to reduce urban overheating is represented by bioclimatic design and passive high albedo (Wang & Akbari, 2014) or "green" solutions (Goussous, Siam, & Alzoubi, 2014).

The investigation of innovative passive low-impact solutions for building energy efficiency in summer are becoming always more important especially in urban areas where more than half of the world's population lives (Paolini, Mainini, Poli, & Vercesi, 2014). In fact, in urban areas, anthropogenic heat released by constructions increases in summer (Gros, Bozonnet, & Inard, 2014) given the huge households energy requirement for cooling (Bellia, De Falco, & Minichiello, 2013) and their increased level of indoor thermal comfort expectation (Moreno, Castell, Solé, Zsembinszki, & Cabeza, 2014).

In this view, building scale and district scale solutions such as urban landscaping, high albedo surfaces and vegetated areas showed to be successful in mitigating urban heat island effect, producing both direct and indirect benefits in urban livability and improvement of building energy efficiency. A specific acknowledged technique in this field is represented by cool roofs (Dimoudi et al., 2014; Gros et al., 2014). These roofs, in fact, present high solar reflectance and high thermal emittance and they are able to reflect the solar radiation, with the consequent reduction of roof overheating and solar gain entering the attic through the roof (Synnefa, Saliari, & Santamouris, 2012). The benefits of this technique have

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been widely investigated all over the world during last decades through both numerical and experimental studies (Kolokotsa et al., 2012). Main results showed important benefits in terms of energy saving for cooling in residential buildings (Synnefa, Santamouris, & Akbari, 2007a) and office buildings (Levinson & Akbari, 2010). Cool roofs and cool materials in general, also present important inter-building benefits at larger scale, by reducing urban overheating especially in dense urban environment (Pisello, Castaldo, Poli, Cotana, & Cotana, 2014; Santamouris, Synnefa, & Karlessi, 2011) and by mitigating global warming (Cotana, Pisello, Moretti, & Buratti, 2014; Cotana et al., 2014b). Given the high potential of cool coatings and cool membranes, which reached competitive cost–benefits balance, the principal application of cool roofs concerned high reflectance materials for application over flat roofs of new or non-historic buildings all over the world, also for the easier and cheaper installation procedure (Bozonnet, Doya, & Allard, 2011).

In this view, the recent registered increase of cooling demand in Italy and the huge amount of cultural heritage buildings in dense urban areas opened the perspective of cool roof application in those buildings which are considered very difficult to improve in terms of energy efficiency, given the rigorous architectural preservation measures. This research lack showed to be even more urgent, since most of historic buildings are located in ancient city centers, typically also affected by local peculiar climate conditions such as urban heat island phenomenon (Busato, Lazzarin, & Noro, 2014; Giannopoulou et al., 2014). In this specific field of application, therefore, cool roof solutions, should be specifically designed in order to preserve the architectural heritage, and at the same time, to reduce cooling energy consumption or to optimize indoor thermal comfort in free-floating conditions. With the purpose to reduce the visual impact of these applications, that are typically light in color (Pisello, Cotana, Nicolini, & Brinchi, 2013; Ferrari, Libbra, Muscio, & Siligardi, 2013), recent research contributions described the elaboration of cool coatings with high reflectance capability but with similar visible appearance to the one of existing traditional roof covering (Synnefa, Santamouris, & Apostolakis, 2007b).

Given the Italian peculiar characterization of roof covering, basically concerning clay tiles for more than 90% of sloped roof surfaces, this key research focus was specifically directed toward the development of "cool" clay tiles with classic visual appearance, in order to be suitable for application in traditional or hedged-in buildings (Pisello et al., 2013; Libbra, Tarozzi, Muscio, & Corticelli, 2011; Libbra, Muscio, Siligardi, & Tartarini, 2012). Particular attention has been paid to historic buildings. In fact, historic buildings in Italy are often occupied by households or public and private offices, where low-efficiency solutions are mainly implemented. Therefore, even larger importance should be dedicated to passive solutions, which could be sufficient by themselves to maintain indoor thermal comfort in many Italian climate conditions. Additionally, in those thermal zones where internal gains are typically not too large, e.g. bedrooms, connections areas, etc. or where the occupancy is limited to specific short periods of the day, strategic passive methods could represent a key improvement solution (Ghaffarian Hoseini et al., 2013).

In this panorama, as already mentioned, given the large majority of buildings with clay tile covering, the study of cool roof solutions suitable for application in historic buildings represents a key environmental issue, in particular for multiple benefits such as (i) cooling energy saving, (ii) reduction of summer peak loads and grid request, and mitigation of climate change phenomena at urban and larger scales.

In this view, starting from previous contribution by the author about the prototyping process of cool clay tiles for historic buildings (Pisello et al., 2013), their comparative performance is evaluated in a typical historic residential building in the city center of Perugia, Italy, located in central Italy temperate climate area. The comparative assessment between traditional and innovative tiles is carried out through calibrated and validated dynamic simulation method. In fact, the case study building has been continuously monitored during summer 2013 in order to calibrate and validate the dynamic simulation model of the palace (4-floor building), where the apartment is located. The thermal-energy assessment is finally operated in order to estimate both summer benefits and winter penalties of the innovative tile in the attic thermal zone. By enlarging the applicability perspective to district level by considering all the residential buildings located within the urban walls of the historic city area, the effect of the proposed tile is also assessed in terms of (i) electricity need for cooling, (ii) consequent reduction of carbon emission and (iii) money saving.

2. Methodology

This research starts from previous findings concerning the elaboration and in-lab characterization of innovative reflective clay tiles for application to existing or historic buildings (Pisello et al., 2013). The most performing tile samples are here collected and described through the dynamic simulation engine (UIUC, LBNL, 2005) and their performance is then evaluated. The building-scale performance of these selected tiles is assessed during the course of the year in order to study their effect in optimizing the attic thermal performance and its energy efficiency by taking into account primary energy requirement for cooling and heating. The case study duplex apartment has been continuously monitored in order to calibrate and validate the dynamic simulation model of the construction, representative of residential construction typicality in historic Italian city centers. Therefore, by assuming similar results in other equivalent historic buildings with residential use, an economic and environmental analysis is carried out. In particular, the corresponding CO_{2eq} emission reduction due to the cooling energy saving is estimated at historic district level.

The detailed research procedure is reported as follows:

(i) Choice of high performing cool tiles, suitable for application in historic buildings, after in-lab analysis and optimization of highly reflective coatings for clay tiles (Pisello et al., 2013).
(ii) Choice of the case study historic building, where implementing the numerical and experimental campaign. The choice was guided by in-situ observation and inspection in order to evaluate the construction typicality of ancient city centers.
(iii) Thermal continuous monitoring of the building by means of thermal probes positioned in the main floor and in the attic, in order to allow the calibration procedure. The main thermal zones of the duplex apartment were monitored, in order to describe both the thermal behavior of the lower and the upper floor, adjacent to the roof, more sensitive to the application of cool tiles.
(iv) Elaboration of the dynamic simulation model and calibration-validation iterative procedure. Materials and boundary conditions were described within EnergyPlus environment and specific iterative calibration procedure was performed. Given the specific considerations on historic buildings, and the lack of information about envelope systems and materials, several assumptions were carried out by mean of in-field analysis.
(v) Selection of the final reliable prediction model, after iterative calibration procedure.
(vi) Year-round thermal-energy performance simulation of 4 scenarios, i.e. the case study apartment with the 4 selected tiles. Indoor thermal behavior and primary energy requirement of the attic were selected as the key variable to study in order to identify the effect of the clay tiles.