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Exploring the potentialities of cool facades to improve the thermal response of Mediterranean residential buildings

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ABSTRACT

Cool materials are characterized by high solar reflectance and by high thermal emissivity, the combination of these two radiative properties allows such construction materials to remain cooler than conventional materials of the same colour under the solar radiation. During the past decades there was a growing interest mainly for roofing and pavements applications, aiming at cooling buildings and cities. This study presents the potentiality of the technology for façade applications in residential buildings, focusing on the performance in the Mediterranean region, where cooling energy uses and urban heat islands are critical issues. The study analyses the performance of cooled and non-cooled buildings by means of dynamic simulations, showing the potentiality of the technology in terms of energy performance and impact on indoor thermal comfort. Calculations are carried out for several building configurations and climatic conditions; also the impact of different solar reflectance values of facades, depending on their orientation, was explored. Cooling energy savings up to 2.9 kW h/m^2 per 0.1 increase of solar reflectance are calculated. The average indoor operative temperature is reduced up to 1.1 °C in non-cooled buildings during the summer period. Average exterior surface temperature reductions up to 7.5 °C, with peak reductions up to 25 °C, are calculated.

1. Introduction

Cool coloured materials are characterised by high solar reflectance (ρ_e), compared to materials of the same colour, and by high thermal emissivity (ε). The former reduces the absorbed solar radiation, and therefore the temperature increase under the sun; the latter enhances the surface cooling by radiative emission of the absorbed heat. These materials thus reduce the heat induced by the solar radiation and released to the built and urban environments by transmission, convection, and radiation. Cool materials were largely used in the past: white and lightly coloured facades are a trademark of vernacular architecture in the Mediterranean area, with shining examples in Greece, Southern Italy, and Northern African shore. Cool materials gained new interest worldwide during the past years as a relevant technology to pursue two main environmental objectives: the improvement of the energy performance and thermal response of buildings and the mitigation of urban heat islands. The relevance of both these issues that cool materials may contribute to counteract is amplified by global warming, which is threatening the future of the planet and making necessary to cool down cities and buildings. The impact of the temperature rise on the thermal response of built environments is well documented (Kapsomenakis et al., 2013; Alcoforado and Andrade, 2008), as well as the impact of the urban heat island on the energy performance of buildings (Akbari and Konopacki, 2005; Santamouris, 2014).

The Mediterranean region, in particular, is experiencing a growth of energy uses for cooling. More in details, cooling accounts for 10% of energy uses in Southern European Countries (Santamouris, 2016); and cooling uses increased by 30% in Spain and Italy in the 2005–2009 period (Odyssee-Mure, 2012). An analysis of energy uses evolution in the 2010–2050 period reports an increase of cooling demand in the 40–70% range (Ciscar et al., 2014). In Southern and Eastern European Countries the penetration of active cooling systems in dwellings is still moderate, but with a significant widespread increasing trend (Missaoui et al., 2012), also amplified by urbanization and population growth. In fact, it is expected that approximately 42 million new dwellings will be built in the area by 2010 (Blue Plan Notes, 2011). In this framework it is crucial to disseminate energy efficiency measures, with particular focus on cooling technologies.

The response of construction materials under the solar radiation in specific climatic conditions is demonstrated in Cheng and Givoni (2005). Reflective materials typically used from vernacular architectures to today building technologies are based on white or light colours to achieve high solar reflectance (Odyssee-Mure, 2012).

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Cool materials solutions, however, evolved through the years, trying to combine energy efficiency, products durability, as well as urban and architectural integration. Recent studies emphasise the importance of the reflection behaviour of the materials in the near-infrared region of the solar spectrum, in order to maintain a higher degree of freedom for the materials' colour (Levinson et al., 2007; Levinson et al., 2005; Synnefa et al., 2007). Novel techniques are recently explored to exploit the potentialities of cool materials, relevant examples are: thermal responsive elements, as PCM doped cool coatings (Karlessi et al., 2011); dynamic envelope solutions, as thermochromic materials (Karlessi et al., 2009; Ma and Zhu, 2009); angular selective materials, as retro-reflective surfaces for construction products (Rossi et al., 2014).

Many studies demonstrate the potentialities of cool materials for roofing applications, namely cool roofs, in reducing the energy end uses in buildings. Numerical analyses can be used to accurately predict the thermal and energy response of buildings, and thus can be used to assess the impact of energy efficient technologies and strategies (Foucquier et al., 2013). Benefits of cool roofs have been extensively investigated, and cooling savings, heating penalties, total energy balance and thermal comfort issues are presented and discussed for different building configurations and climatic conditions (Taha et al., 1988; Dias et al., 2014; Synnefa et al., 2007; Mastrapostoli et al., 2014; Zinzi, 2010), as well as the influence of ageing (Paolini et al., 2014). Thermal response and energy efficiency of cool roof solutions were also explored by case studies, direct or by means of calibrated simulations (Akbari et al., 1997; Akbari et al., 2005; Jo et al., 2010; Pisello and Cotana, 2014; Rosado et al., 2014; Zinzi and Fasano, 2009). The performance of cool roofs is explored in terms of different parameters, such as: indoor air or operative temperature evolution, outdoor surface temperatures, energy savings achieved by different cool roof solutions. These studies are carried out for residential and commercial buildings in different continents and climatic conditions, also different cool technologies were investigated.

Cool materials also gained interest for urban applications, to reduce surface and ambient temperatures, thus mitigating urban heat islands and, in an indirect way, reducing the thermal stress in buildings. The development of new materials and the impact of the technology are documented in several studies (Pomerantz et al., 2000; Synnefa et al., 2011; Akbari et al., 2001; Carnielo and Zinzi, 2013; Levinson and Akbari, 2002). Outcomes of these studies include: solar reflectance of reflective materials for pavements, impact on the ambient temperatures, and potentialities of urban heat island mitigation.

A comprehensive review about cool material studies is carried out in Hernández-Pérez et al. (2014), where also façade applications are analysed. Theoretical studies addressed the impact of the solar reflectance of the building envelope on the energy performance and thermal response of buildings in Mediterranean climates (Ascione et al., 2010; Shariah et al., 1998; Eskin and Türkmen, 2008), and some experimental studies relied on test cells (Revel et al., 2014; Pisello et al., November 2015). In both cases the impact of the solar reflectance variation on the energy performance is explored. However, a systematic analysis to assess the impact of cool façades on the energy and thermal comfort performance of buildings is still missing. The issue is worth of investigation, especially for the Mediterranean area, which is experiencing the effect of the above cited climate changes and temperatures rise, as well as a dramatic increase of energy end uses for cooling. Potentialities and limits of the technology and its application are addressed in this study.

2. State of the art of cool materials for façade applications

If a significant body of work is carried out about cool materials' applications for roofs and urban pavements, the same does not apply to facade applications, shortly called onward cool façades. White and light coloured materials are used for façade applications since centuries, as witnessed by white villages and town scattered across the Mediterranean region, shining examples of vernacular architecture. New solutions were, however, investigated during the past years, with the objective of improving the cooling energy performance of building envelopes, without the architectural limitations of façades finished by too light colours. Acrylic based masonry cool coloured finish coats with quartz filler, in dark and pastel colours, were designed to reduce the thermal stress on external thermal insulation composite systems (Zinzi, 2016). Acrylic cool coloured paints were also developed and tested in a study which also involved the development of cool ceramic tiles (Revel et al., 2014). The latter was of particular interest, since it was necessary to develop cool pigments stable at the high temperatures, typically around 1200 °C, as well as to optimise the design process, including composition and thicknesses of base and topcoats. Advanced ceramic cool materials were investigated also in Ferrari et al. (2013). The technological solution is a conventionally manufactured cool white tile, where the engobe works as basecoat and the glaze is the near infrared topcoat. Different solutions, in terms of base material and formulation, were developed, reaching solar reflectance values up to 0.9. In a next step cool coloured glazes for tile finishing were developed, which is crucial for façade applications as white tiles can be seldom used. High near infrared reflectance were measured, as well as solar reflectance up to 0.6 was measured for a grey sample, showing the potentiality of the technology for building applications (Ferrari et al., 2015). Metallic cool coloured alternatives were developed with anodized aluminium and aluminium with reflective baked-on coatings in different shades of brown, with a solar reflectance up to 0.5 for a light brown samples, for instance (Ihara et al., 2016). Relevant for façade application is a study on the performance of mineral based coatings, even if limited to white samples (Kolokotsa et al., 2012). High solar reflectance and emissivity values were measured for renders, based on lime with additions of calcium carbonate powder, and for paints, based on lime wash or silicate minerals. Of particular interest is the work on renders, finishing technology widely used in the Mediterranean building stock.

It has also to be noted that advanced materials, already mentioned in the previous section (Karlessi et al., 2011; Karlessi et al., 2009; Ma and Zhu, 2009; Rossi et al., 2014), represent potential applications for building façades.

3. Objective and method

This study aims at investigating the impact of cool facades for residential buildings' applications, narrowing the climatic framework to the Mediterranean region, which is characterized by comparable dwelling stock technologies and similar environmental concerns, even if with different intensities in the specific countries. The assessment is carried out by means of numerical analyses, as a function of the main variables that affect the building energy performance and the potentialities of the cool façade technology. Three main aspect are investigated:

- Net energy use for cooling and heating in conditioned buildings. Net energy is intended as the energy supplied by an ideal lossless energy system to keep the building air temperature at the set-point value. Final and primary energies are not taken into account, avoiding the introduction of efficiencies of energy systems and focusing the results on the thermal response of the building envelope. The approach is in line with the EU nearly zero energy buildings, where the design of the building envelope will require a small contribution of the active systems, whose energy use will be mainly covered by renewable energy sources.