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Review

State of the art on the development of cool coatings for buildings and cities

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ABSTRACT

Urban systems, from their early origins, were acknowledged to be responsible for both benefits and penalties due to anthropogenic actions affecting human wellbeing. In this view, local overheating exacerbated by urban heat island phenomenon has been identified as a result of anthropogenic actions responsible for citizens' health issues and other serious socio-economic consequences in urban areas, where almost the 70% of the world population is expected to live in thirty years. This fact imposes to respond to an urgent research question concerning the development and the real-world application of effective mitigation strategies against urban climate change phenomena, for a better population resilience. Among the variety of these strategies, the implementation of "cool" coatings over urban surfaces exposed to the solar radiation, i.e. cool roofs and cool pavements, represents a proved solution to counteract such overheating effect and its negative consequences on the population living in urban context. In this view, the present work reviews the state of the art about the development of new materials and their main applications as cool roofing and paving systems for passive cooling purpose of buildings and cities, which have been published in more than 260 papers in the last decades. Both indoor and outdoor passive cooling benefits were clearly demonstrated and quantified with varying climate conditions, material characteristics and the built environment context. Despite that, the investigation around this issue is still active worldwide, from chemistry, material science and engineering fields. Additionally, new triggers were highlighted as possible starting points for future scientific focus. In particular, still active discussions give rise to promising research findings expected to clarify (i) the effect of cool coatings on pedestrians' glare, possibly mitigated by directionally-reflective materials, (ii) the role of cool coatings for HVAC optimization, (iii) the combined benefits of cool coatings and thermal-energy storage techniques for UHI mitigation.

Contents

1. Introduction 661
2. Cool coatings indoor-outdoor behavior. 662
3. The cool coating concept 663
   3.1. Solar reflectance and infrared emittance 663
   3.2. Solar reflectance index 664
4. Materials for cool coatings. 664
   4.1. Cool roof and cool façade coatings 664
   4.2. Cool roof paintings 664
   4.3. Cool waterproof membranes 665
   4.4. Cool tiles 665
   4.5. Cool natural materials 666
5. Multiple effects of cool coatings applications 666

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5.1. Cool coatings for cooling energy saving 666
5.1.1. Residential buildings 666
5.1.2. Commercial buildings 667
5.2. Cool coatings for urban heat island mitigation 668
5.3. Cool coatings for indoor thermal comfort optimization 669
5.4. Cool coatings for outdoor thermal comfort optimization 669
5.5. Cool coatings for optimizing HVAC and PV performance 670
5.6. Cool coatings durability and life-cycle performance 671
5.7. Cost-benefit analysis of cool coatings 672
6. Statistics on cool coatings 672
7. Concluding remarks 674
Acknowledgements 675
References 676

1. Introduction

From their early origins, urban systems have produced both benefits of penalties due to anthropogenic actions (Pain, 2016). Some risks have been successfully tackled while other new ones are increasingly making urban citizens more vulnerable. Anthropogenic heat release represents an added energy input to the energy balance (Zhao et al., 2014; Ward et al., 2013) in cities, responsible for the urban surface temperature increase, i.e. the world-wide known phenomenon of Urban Heat Island (UHI) Allen et al., 2011; Fischer and Schär, 2010.

Lindberg et al. (2013) estimated the quantitative consequences of the anthropogenic heat excess in cities through the global anthropogenic heat flux (Q_F) model LUCY (Large scale Urban Consumption of energY model), allowing them to identify a general relatively low Q_F around European territory (i.e. about 1.9–4.6 W m^{-2}), but with urban maximum peaks up to around 80 W m^{-2} simulated in London dense boroughs. Such excess of anthropogenic heat showed to be responsible for massive increase of energy need for cooling in summer, up to 13%, and on the other side, the decrease in energy consumption for heating in winter corresponded to around 11%. Such urban energy balance variation and extra-carbon emissions in densely populated areas are identified as key consequences of the urban heat island (UHI) phenomenon. UHI has been widely acknowledged as a direct responsible for citizens' health issues (Patz et al., 2005; Li et al., 2013) and other serious socio-economic and energy consequences in urban areas (Harlan et al., 2006; Santamouris, 2016; Wang and He, 2014), where almost 85% of the world population is expected to live in 2100 (World Urbanization Prospects, 2014) and where almost 80% of the total CO_{2eq} emissions are produced (Pérez-Lombard et al., 2008). The acknowledged consequences of dense and rapid urbanization, with the following decrease of natural landscape, basically concerns the massive modification of the local energy balance due to the implementation of radiative absorbent and non-permeable surfaces that tend to minimize their capability to reflect heat much more than forests and planted areas and, therefore, being responsible for the dramatic increase of urban surface and air temperature (Santamouris and Kolokotsa, 2015). In this view, Urban heat island (UHI) is the most acknowledged climate change related phenomenon, which has been documented through a wide variety of experimental and simulation studies (Neophytou et al., 2014; Kusaka and Kimura, 2004; Richiardone and Brusasca, 1989) aimed at investigating overheating path of urban temperatures with respect to the relatively colder conditions of suburban areas (Chen et al., 2016; F. Chen et al., 2014; C. Chen et al., 2014). Such phenomenon has been also acknowledged for being responsible for serious socio-economic and health issues making city citizens more vulnerable to climate change and less resilient to its consequences (Santamouris and Kolokotsa, 2015; Pyrgou et al., 2017; Heaviside et al., 2016). The situation becomes even more urgent knowing about the rapid gathering of population in urban areas, and the consequent need for cheap and readily available dwellings, where indoor environmental low quality and energy poverty showed to hugely compromise occupants' health conditions and comfort during extreme climate events (Hatvani-Kovacs et al., 2016a, 2016b, 2016c), e.g. heat waves (Graham et al., 2016; Ward et al., 2016).

In this perspective, a massive scientific effort has been dedicated to the proposal of geo-engineering based solutions for effectively mitigating climate change phenomena, such as UHI (Akbari et al., 2016; Akbari and Muscio, 2015). Among these solutions, the proposal of high albedo materials for urban paving and building envelopes has been proving key achievements during the last decades, as effective measure for counteracting urban warming by increasing the solar reflectance of urban surfaces and, therefore, urban solar heat gain (Wang and Akbari, 2015). High albedo surfaces are typically characterized by "cool" coatings applied over building roofs and outdoor pavements, considering the large potentiality of such surfaces to contribute to UHI mitigation. In fact, roof surfaces in urban areas may correspond to about 20–40% of the total area exposed to solar radiation, while the paved area correspond to 29–44% of the total (Akbari and Matthews, 2012; Xu et al., 2012b), meaning that the implementation of cool coatings could be massively handled with promising local and global benefits energy and environmental benefits.

The key benefits of cool coatings when applied over building envelopes and urban pavements basically consist of the improvement of indoor and outdoor thermal comfort conditions in summer with evident contribution at several scales: such as the indoor-outdoor microclimate scale and the mesoclimate scale, together with the global climate one (Cotana et al., 2014b; Rossi et al., 2013; Akbari et al., 2012, 2009b). At the same time, if the cool coating is also applied over building roofs and facades, it can lower the energy need and the CO_2 eq emissions for cooling imputable to the HVAC operation or, as passive cooling technique, it can improve indoor thermal comfort conditions in summer (Pisello et al., 2016c; Wang et al., 2016). Therefore, cool coatings can be effective measurements for counteracting the increasing trends of (i) cooling energy in urban areas, (ii) air pollution and ozone concentration in cities (Sheng et al., 2017), and (iii) urban carbon footprint (Rossi et al., 2016a).

Despite the consistent agreement about the effect of high albedo solutions for indoor-outdoor overheating mitigation, the effectiveness of cool coatings is sensitive to both UHI characteristics and building features where they are applied. In particular, UHI represents a complex phenomenon, depending on a variety of factors such as: local weather boundary, geomorphology, urban layout, anthropogenic heat intensity, urban vegetation design, characteristics of building skins and, more in general, of the whole