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Green and cool roofs' urban heat island mitigation potential in tropical climate

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ABSTRACT

Urban heat island (UHI) can significantly affect building's thermal-energy performance. Urban materials absorb solar and infrared radiation and the accumulated heat is dissipated in the atmosphere increasing further the air temperature. Roofs are envelope components which with advanced solutions such as cool roofs or green roofs can provide significant energy savings in air-conditioned buildings and improved indoor thermal conditions. By means of dynamic simulations in EnergyPlus software a numerical comparative analysis between these two solutions was done in a tropical climate like Singapore's, taking into account climatological, thermal, optical and hydrological variables.

Simulations of a typical summer day in Singapore were assessed to determine (i) UHI reductions for different green/cool roof scenarios; (ii) the diurnal heat fluxes dynamics and (iii) the buildings' thermal energy reduction for the investigated cases.

The results show that during peak periods (9 am to 5 pm) cool roofs reduce heat gain by about 0.14 KWh/m^2 (8%) and green roofs mitigate considerably less to about 0.008 KWh/m^2 (0.4%). And for the whole of a summer design day, cool and green roof reduces heat gain by 15.53 (37%) and 13.14 (31%) KWh/m^2 respectively.

The numerical simulation results confirm that an appropriate selection of roof materials contribute to the reduction of the negative effects of UHI but experimental data for air-conditioned buildings are yet to be carried out.

1. Introduction

The temperature difference between urban and rural areas, a phenomenon known as urban heat islands (UHI), has been the subject of extensive research over the past decades (Oke, 1982; Santamouris et al., 2014; Santamouris, 2015). The decrease in vegetation, increasing urbanization, and steep rise of population over the last century has led to an elevation in urban temperatures that exacerbate the phenomenon, in addition to its adverse association with thermal discomfort and endangerment of human health (Cartalis et al., 2001)) and it has caused more than 150,000 lives annually according to the World Health organization (WHO, 2005).

Especially the energy consumption for cooling buildings has increased tremendously in recent years (Asimakopoulos et al., 2012; Oikonomou et al., 2012). According to the International Energy Agency, on a global-scale, buildings account for 30–40% of worldwide energy consumption. In Singapore, about 50% of total electricity produced goes into buildings and for cooling alone buildings use about 30% of the country's total electricity production (Tan et al., 2010). The increase of urban temperatures that increases overheating risk and indoor thermal discomfort is greatly influenced by the sensible heat flux and energy storage of the construction materials (Pyrgou et al., 2017; Salata et al., 2015; Santamouris et al., 2014; Santamouris, 2014a). Roofs of buildings constitutes about 20–25% of urban surfaces. Studies found that the solar radiation impinging on the roofs can easily raise their outer surface temperature up to 50–60 °C (Andrade et al., 2007). To negate the above conditions the most common urban heat mitigation technologies associated with roofs are: (a) the cool (or reflective) roofs, and (b) green roofs (Yang, 2017).

The surface energy fluxes contribute to the Earth's mean energy

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budget and can assist in the explanation of the mitigation mechanisms. The net radiation (Q*) may be defined as:

$$Q^* + Q_F = Q_H + Q_E + \Delta Q_S + \Delta Q_A \quad (1)$$

where Q_H, Q_E and ΔQ_S are the sensible, latent and conduction/storage heat fluxes respectively. Anthropogenic heat (Q_F) is fairly difficult to calculate and depends on energy consumption within buildings and transportation. The net heat flux by horizontal advection (ΔQ_A) has values close to zero and therefore is not considered. Cool roofs mitigation effect focuses on the decrease of the net radiation Q* by the increase of albedo of the urban surface (Li et al., 2014; Roman et al., 2016) and the decrease of the sensible heat flux and heat storage. Assuming a steady net radiation Q*, green roofs increase the latent heat flux compared to the sensible heat flux and the heat storage into the buildings and therefore leading to lower energy demands for cooling for the building. Latent heat loss is accomplished via either the transpiration of the plants or the evaporation of moisture from the soil, resulting to lower surrounding air temperature and a net cooling effect (Tian et al., 2017). Both these mitigation strategies aim to lower the roof surface temperatures thereby decreasing the sensible heat flux released to the atmosphere.

Cool roofs traditionally use natural white materials or second generation materials like artificial white paint to reflect the most of the incoming solar radiation and thereby decrease the net radiation within the building. They have performed better at reducing cooling loads within buildings when compared to conventional roofs (Doulos et al., 2004; Kolokotsa et al., 2012a, 2012b; Synnefa and Santamouris, 2012) leading to decreased air conditioning needs and improved indoor thermal comfort. Recent advancements in the field of cool coatings has paved way to thermo chromic paints, PCM doped coatings and advanced colored materials that use infrared reflective pigments. These present higher reflectivity compared to conventional materials and contribute to better performing buildings (Akbari and Levinson, 2008; Karlessi et al., 2011, 2009; Kolokotsa et al., 2012a, 2012b; Synnefa et al., 2011, 2007). Cool coatings can be applied both on existing and new roofs and they are environmentally-friendly as they don't add any additional waste.

Green roof typically is a vegetative layer with a growing medium, like soil, over a waterproofing membrane. There are two distinctive types in green roofs; extensive and intensive. Extensive roofs are cost-effective and easy to maintain, having a thin layer of low-growing vegetation and a shallow soil layer. Intensive green roofs require very high maintenance and heavy construction for support as it includes a deep growing medium and high-growing medium such as trees and shrubs. Green roofs are used globally for the insulation of buildings (Oberndorfer et al., 2007), as they enhance heat transfer through roofs and provide steadier outside roof temperatures in cold winters and hot summers (Jaffal et al., 2012; Tian et al., 2017). Additional cooling effect in green roofs can be obtained by increasing soil moisture through irrigation (Li et al., 2014). Creating green roofs on buildings requires a deep investigation of the most appropriate soil composition and height to ensure adequate drainage with respect to the existing weather conditions and whether the building can withhold the extra load. The many advantages of green roofs include decreased energy consumption within the buildings by reducing absorption of solar radiation (has higher reflectivity compared to normal roofs) and evapotranspiration of plants and insulation of buildings, reduction in UHI, improved microclimate, better air quality, reduced air pollution and greenhouse gas emissions as the plants remove the air pollutants through carbon sequestration, increase water-permeable city surface, enhanced stormwater management and increased durability of roof materials.

The studies conducted in the United States and Europe quantified the heat gain reduction, heat fluxes reduction and the thermal effect in these climate zones (Akbari and Konopacki, 2004; Kolokotroni et al., 2013; Kontoleon and Eumorfopoulou, 2008). A few studies have also been carried out in tropical climate (Zingre et al., 2015) to evaluate the use of cool roof and green roof at the location with abundant annual-averaged solar irradiation. Various boundary conditions (heat fluxes or heat transfer coefficients based on thicknesses and materials) affect the heat and moisture exchange between surface and atmosphere. The utilization of various scenarios of green/cool roofs in different locations in the world with variating boundary conditions result in differences in the surface energy balance (Sharma et al., 2016) and indoor air temperatures. In conventional roofs, incoming energy is mostly translated into sensible heat flux increasing the surface's surrounding air temperature. Kolokotsa et al. (2012a, 2012b) made a comparative analysis of cool roofs and green roofs in Crete, Rome and London with respect to a conventional roof, revealing higher mitigation potential of UHI for albedo higher than 0.6 for cool roofs and leaf area index higher than 1 for green roofs (Kolokotsa et al., 2012a, 2012b). Meteorological conditions and sunshine duration of tropical regions differ than climates in Europe (Mediterranean, subtropical or polar) and the US (subtropical, monsoon, arctic, Mediterranean) resulting to different boundaries and indoor air temperature behaviour. Particularly, high temperatures and high air moisture, apparent in tropical areas, affect the green roof performance because when the green roof is at a higher level of moisture than its field capacity, water will drain even if the roof is not irrigated. However, the overall energy performance of the two techniques has not been examined with different parametric and constructional characteristics under tropics and further investigation is needed.

From the literature review part above, the comparison of cool roof and green roof in detail is not studied for tropical climate. The purpose of this paper is to observe the heat fluxes and the thermal effect of cool and green roof for future design purposes and current design modifications for tropical climate through computer simulations only. Specifically, the scenarios studied evaluate the diurnal heat fluxes using recent meteorological data and variating properties for cool and green roofs in tropical climate.

2. Area of study

According to Singapore meteorological data from 1980 to 2010, Singapore is a tropical island country with mean outdoor temperature of 28 deg C (minimum 24 to maximum 32 deg C) and 84% outdoor relative humidity. Singapore shows a steady climatic condition throughout the year. Simulations have been carried out majorly for a summer design day as temperature vary very little from month to month and day to day as the proximity of the sea has a moderating influence on its climate. In the last 50 years, there has been a rapid development in Singapore with farms and forest areas diminishing and built-up area increasing from 28 to 50% from 1955 to 1998 (Chow and Roth, 2006). Due to this, roof area exposed to solar radiation has increased and the Government has set targets to cover their roofs with cool or green roofs by 2030 to bring about a positive change in their climate.

3. Variables affecting behaviour of cool and green roofs

Santamouris (2012) and Kolokotsa et al. (2013), identified four broader variables that influenced the behaviour and performance of the cool and green roofs (Kolokotsa et al., 2013; Santamouris, 2014b).

3.1. Climatological variables includes

- Intensity of solar radiation that determines heat storage, surface temperature and thermal balance of roofs.
- Ambient temperature that determines the sensible heat released by roofs.
- Ambient Humidity and precipitation that determines the moisture balance in green roofs.
- Wind speed and atmospheric turbulence that determines heat transfer coefficient between the surface and atmosphere.

3.2. Optical variables includes