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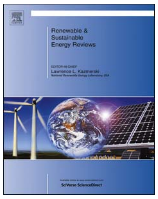

Outdoor thermal comfort by different heat mitigation strategies- A review

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ABSTRACT

Due to the ongoing global warming, heat mitigation strategies are becoming implemented through practice and simulations. These efforts aim to make the cities that are dealing with the urban heat island more livable. The effect of heat mitigation strategies on climate 320condition and energy consumption have been studied and compared, previously. In this paper, the effect of these strategies on human thermal comfort in urban open spaces is reviewed. Specifically, the review is focused on vegetation (in the form of parks, street trees, green roofs and green walls), and highly reflective materials (on roof and on the ground level) as the most common strategies for improving the thermal conditions in cities. Several studies done by simulation or through field measurement in different countries are described. The most important finding of the review is the fact that although highly reflective materials reduce air temperature in urban open spaces, they increase the re-radiation of sun to the pedestrians. Therefore, vegetation is a better choice for improving thermal comfort in the pedestrian level.

1. Introduction

The air temperature in most of the cities are significantly higher than their rural areas. This phenomena which is called urban heat island (UHI) causes negative issues for urban settlers. UHI was first identified by Luck Howard, a meteorologist who measured the weather in London area for forty years (1801–1841) [1]. The UHI happens throughout the year, but it is stronger during the night when heat is absorbed by the urban surfaces with high heat capacity materials (e.g. asphalt and concrete). Apart the heat capacity of man-made materials, urban canyons reduce natural ventilation and therefore heat traps in cities. The intensity of the UHI is also related to the size and population of the city [2–5]. Oke [2] showed that UHI is approximately proportional to the fourth root of the population. This shows with the increase of urban settlers, more people are in prone to UHI. Since 2008, more than half of the world's population live in cities [6]. But, what are the consequences of UHI for citizens?

Higher air temperature has direct and indirect effects. The most direct effect of UHI is lower thermal comfort of people in urban spaces, where there is no access to air conditioning systems [7–11]. UHI indirectly increases energy consumption for cooling [12,13], reduces the air quality in cities [14–18], and threats the ecosystem by warmer water flowing from the cities [19,20].

As heat waves are the first natural cause of mortality [5,21–25], this research focuses on the impact of UHI on thermal comfort of people in urban open spaces. During a two week heat wave in August 2003, 70,000 people passed away [22]. Heat related mortality occurs when human body absorbs more heat than it dissipates. This is more serious for elderly and people with cardio-vascular problems who have weaker thermoregulatory body system [25]. Several studies have shown strong correlations between heat waves and excess mortality [21,23,26]. In this way, making cities cooler seems vital for public health.

Thermal comfort is associated with environmental (air temperature, radiant temperature, wind speed, and relative humidity) and personal (clothing and metabolism) factors [7,27–30]. Several studies have shown that radiation plays the greatest role on thermal comfort [28,31–34]. In [35–40], the impact of urban morphology and different heat mitigation strategies on urban climate have been reviewed. Due to the significant role of radiation on thermal comfort, in this paper we focus on the heat mitigation strategies that reduce net radiation in urban spaces. Eq. (1) describes the variables affecting net radiation [41]:

$$Rn = H + LE + G \tag{1}$$

where Rn is net radiation, H is sensible heat flux, LE is latent heat flux, and G is soil heat flux (all variables are in W/m^2.

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Several heat mitigation strategies have been implemented in different cities to reduce net radiation. Theoretically, the lower net radiation, the lower heat in cities. Based on this principal vegetation and reflective materials are widely used as passive methods to mitigate heat in urban spaces. Here we review these strategies extensively. Therefore, the paper will focus on the most recent studies that have successfully implemented heat mitigation strategies in the world. Specifically, vegetation and high albedo materials will be studied in different form of application. The reviewed studies have used different methods (i.e. simulation and measurements).

2. Heat mitigation strategies

2.1. Vegetation in different forms

Vegetation reduces heat in three ways:

a) by evapotranspiration,
b) by reflecting the sun because of the higher albedo of the leaves compared to man-made dark materials;
c) by blocking the solar radiation.

Vegetation has been used in various ways in cities. From a large to local scale, we can see vegetation in cities as parks, street trees, grass yards, and green roofs.

2.1.1. Parks

Parks probably have the biggest cooling effect for citizens. Hwang et al. [42] in a study on 10 parks in the tropical climate of Singapore showed that the air temperature in parks could be 8–12 °C cooler than outside. They showed the parks with more shading are more thermally comfortable. This finding becomes more important when we consider that the minimum temperature in Singapore is 23 °C [43].

Looking at the hot and dry climate, parks seem very vital for public health. Feysia et al. [44] by measuring air temperature and humidity in 21 parks in Addis Ababa showed that plant types, NDVI (Normalized Difference Vegetation Index), and shape and size of the parks have appreciable correlations with the cooling effect. The maximum park cooling effect (PCI) they found was 6.72 °C. Moreover, they measured the maximum spatial park cooling distance (PCD), which was 240 m. This means the cooling effect of a park could be felt up to 240 m far from the park. By comparing different plants (i.e. Acacia tortilis, Eucalyptus spp., Grevillea robusta, Cupressus lusitanica and Olea), they showed Eucalyptus spp has the most cooling effect; while Grevillea and Cupressus have the minimum effect.

Spronken and Oke [45] studied the PCI in two cities with different climates, Vancouver (BC) and Sacramento (CA). They showed the maximum cooling effect in Vancouver was 5 °C; while irrigation of the park in Sacramento (with a hotter climate) makes the PCI up to 7 °C. They found out the trees are the most important element for the cooling effect of the parks during the day. This was due to the shading and evapotranspiration effect of the trees. During the night, the amount of moisture and surface geometry of the parks were the most important causes of PCI.

Vidrih and Medved [46] considered the effect of leaf area index (LAI) on the cooling effect of parks in Slovenia. By using a 3D CFD model, they showed that with the LAI of 3.16 (equal to 45 trees per hectare), air temperature reduction is up to 4.8 °C. In a more comprehensive and empirical study done by Hardwick et.al [47], the effect of different levels of LAI on different micrometeorological variables were studied in Malaysia. They found a strong correlation between LAI and the mean daily maximum air and soil temperatures. They also showed a higher cooling effect associated with higher relative humidity under vegetation canopies with higher LAI. They also showed a canopy with 33.7 m height is 6.5 °C cooler than oil palm plantations with 5.3 m height. Fig. 1 shows the surface temperature of the park of the campus of Portland State University compared to the buildings.

2.1.2. Street trees

Street trees have several environmental benefits for urban citizens. Because of our focus on thermal condition and comfort in urban open spaces, we review the most important investigations on thermal comfort. Coutts et al. [49] measured three east-west streets during heat waves in the temperature climate of Melbourne, Australia. They considered the Universal Thermal Climate Index (UTCI) for the calculation of outdoor thermal comfort within the tree canopies. The maximum UTCI reduction by the trees were 6 °C. Moreover, they reported that the maximum air temperature reduction was 1.5 °C. A similar research done in Melbourne showed that Platanus trees led to a PET reduction of 6.6 °C during a heat wave.

Regarding the cooling effect of different tree species, Doick and Hutchings [50] discuss that the lower the foliage temperature, the greater cooling effect. Monteith and Unsworth [51] argue that the leaf temperature depends on anatomical (e.g. LAI and size) and physiological (e.g. transpiration and stomatal conductance) factors. In this way, the water status (i.e. irrigation) will have a significant effect on the ability of a tree to evaporate water through the stomata of its leaves [52].

Another advantage of street trees is their impact on their adjacent. Mayer et al. [53] showed that trees reduce mean radiant temperature (T_{mrt}) even for the buildings that are not shaded by the trees. In the city of Freiburg (Germany), they showed that trees reduce T_{mrt} up to 29% at the not directly shaded site. This amount of radiation reduction is very important for the improvement of pedestrian's thermal comfort. This is mainly due to the dependency of thermal comfort on T_{mrt} [28,32]. This reduction of radiation can improve the thermal comfort of people inside the adjacent buildings. For instance, Heisler [54] showed that a sugar maple tree reduced irradiance by its shading effect up to 80% in summer (when in leaf) and 40% in winter (leafless).

2.1.3. Green roofs

Santamouris [55] reviewed the impact of green roofs on UHI. By comparing different simulation studies, he found out that green roofs can reduce the average air temperature between 0.3 and 3.0 K when applied on urban scale. Depending on the adoption scale, the cooling effect varies. Smith and Roebber [56] studied the adoption of green roofs during a typical summer day in Chicago, Illinois. They used the Weather Research and Forecasting Model (ARW) [57] coupled with an urban canopy model. In accordance with [55], they showed that the air temperature during 19:00–23:00 is reduced up to 2–3 °C because of the higher albedo of the vegetative roofs, and the evapotranspiration effect. Fig. 2 shows a green roof with its layers.

Sun et al. [58] investigated the temperature reduction over a roof (2.5 m) in Taipei. They showed the cooling effect of the green roof was more significant during day time. Comparing the green roof with a similar black roof, the green roof reduced the ambient air temperature 0.26 °C in average. The maximum cooling effect was reported 1.6 °C.

Chen et al. [59] performed simulations on the impact of high rise buildings green roofs on the pedestrian height (1.5 m) thermal condition in Tokyo, Japan. For the simulations, they used coupled simula-