Building and Environment 130 (2018) 49–61

Contents lists available at ScienceDirect

Building and Environment

journal homepage: www.elsevier.com/locate/buildenv

Comparing the cooling effects of a tree and a concrete shelter using PET and UTCI

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ARTICLE INFO

Keywords:
Cooling effect
Thermal benefit
Urban tree
Physiological Equivalent Temperature (PET)
Universal Thermal Climate Index (UTCI)
Outdoor thermal comfort

ABSTRACT

Trees could provide notable cooling by intercepting solar radiation and evapotranspiration. Human-made shelters in urban areas also serve as shading devices. However, few studies have compared the cooling efficacy of trees and artificial shelters. This study systematically quantified and compared the daytime and nighttime cooling effects of a large Chinese Banyan tree (*Ficus microcarpa*) with dense foliage and an extensive concrete shelter, in an urban park in Hong Kong's subtropical summer. Microclimatic parameters at the two sites were monitored to compare air temperature, and the computed values of PET (Physiological Equivalent Temperature) and UTCI (Universal Thermal Climate Index). The mean daytime cooling effects generated by the tree were 0.6 °C (air temperature), 3.9 °C (PET) and 2.5 °C (UTCI), which were higher than the shelter at 0.2 °C, 3.8 °C and 2.0 °C respectively. The differences were significant for air temperature and UTCI ($p < .001$ and $p < .05$ respectively, *t*-test) but not for PET ($p = .261$). The tree's mean daytime maximum cooling effects were 2.1 °C (air temperature), 18.8 °C (PET) and 10.3 °C (UTCI). The tree's mean nighttime cooling was significantly higher than the shelter for all three indices ($p < .001$, *t*-test). The thermal stress classifications by PET and UTCI were significantly different on the neutral or warmer side ($p < .001$, Chi-squared test), suggesting that they cannot be used interchangeably. The findings could inform decisions on natural versus artificial shelters in urban thermal design, and trigger comparative investigations in using PET and UTCI for outdoor thermal comfort assessment.

1. Introduction

Urban development is often characterised by the conversion of reflective and evaporative surfaces such as trees and vegetated areas, to dark and heat-absorbing surfaces such as concrete and asphalt [1,2]. These human-made materials can absorb and store substantially more solar energy than vegetation. The absorbed energy will dissipate into the urban environment mainly as sensible heat to raise air temperature of the city [3]. City temperature may further increase with global warming. The Intergovernmental Panel on Climate Change (IPCC) [4] estimated that, compared to the average between 1850 and 1900, the world surface temperature is likely to rise over 1.5 °C by the end of this century, assuming an intermediate CO_2 emission scenario (RCP 4.5).

One of the major consequences of increased urban temperatures is stronger outdoor heat stress [5–7]. The results of thermal stress mapping of subtropical Taipei [8] and Hong Kong [9] showed that intensely built areas could be 4 °C PET (Physiological Equivalent Temperature) higher than the adjacent less developed areas or urban green spaces. The difference corresponds to about one step of increase in thermal stress on PET's 9-level scale [10]. The thermal impact of climate change is anticipated to intensify and spread. It was estimated that PET could increase over 15 °C in the Mediterranean and North America by 2100 if humanity continues to adhere to a fossil fuel intensive economic style [5]. With urban population potentially exceeding 70% of the world's population by 2040 [11], controlling heat stress in cities is important to reduce the risk of heat-related morbidity and mortality [12,13].

Introducing green vegetation into the urban environment is recognised as a cost-effective nature-based solution to mitigate the warming effects [14–18]. Vegetation can be incorporated into a city's landscape in four major forms [14], namely green open spaces [19,20], trees [21–26], green roofs [27,28] and green walls [29–31]. Trees planted at the pedestrian level are particularly useful to reduce thermal stress compared to other types of greening [16,32–34]. This is because leafy trees can intercept a significant amount of solar radiation [35], which is the most influential meteorological parameter on thermal stress [36–39]. Even the shade of small trees with medium leaf density was capable of reducing thermal sensation from the 'very hot' category down to 'comfortable' in the ITS (Index of Thermal Stress) scale [37]. Both empirical and modelling studies have shown that, even in a treed urban canyon and in urban parks, the heat stress at exposed spaces can

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https://doi.org/10.1016/j.buildenv.2017.12.013
Received 23 October 2017; Received in revised form 12 December 2017; Accepted 14 December 2017
Available online 16 December 2017
0360-1323/

be as high as if there is no vegetation [32,40,41]. Therefore, it is essential to plant shade trees or provide shading structures to improve the thermal environment of uncovered spaces, including urban green spaces [15,41–44].

Previous studies on the cooling effects of urban vegetation have focused mainly on trees and grasses [21,25,40,45–47]; few have compared greenery with human-made shading structures [48]. Solid shading structures are likely to reduce more incoming solar radiation than a single tree canopy, but air temperature reduction can be notably realised with the combined effects of shading and transpiration of living plants [49–51]. The comparative microclimatic benefits of trees and shading structures are largely unknown. Understanding the thermal effects of different landscape elements is particularly important in the design stage of urban green spaces [22,44]. A good landscape design that optimises the thermal environment of the green space may directly improve their utilisation and quality of recreational experience [42,52].

In view of the above-mentioned knowledge gap, this study aimed to measure and compare the cooling effects of a large tree and a human-made shading structure in an urban park in the hot season of Hong Kong. The cooling effects were measured and compared with reference to two commonly used human thermal indices, PET and UTCI (Universal Thermal Climate Index), as well as air temperature. As there is limited empirical research comparing the behaviours of the two biometeorological indices [53,54], their differences in application particularly in the classification of heat stress, were examined.

2. Materials and methods

2.1. Study area

Hong Kong is situated at the south coast of China. Its climate is characterised by a distinct rainy hot summer and a dry mild winter (Köppen climate classification: *Cwa*). The average temperature is 23.3 °C (1981–2010) and the average annual total rainfall is 2398.5 mm [55]. The study location is an urban park in Kowloon Bay (22.32° N, 114.20° E), which has been developed in recent decades as an industrial and commercial area in Hong Kong. The park occupies an area of 1.47 ha (approximately 120 m × 120 m). It consists of a 3-storey concrete building on the north corner, a timber decking on the east and a large lawn on the south [56] (Fig. 1a). Although there is a 126.3 m tall building to the east (Fig. 1b) and another 170.0 m building to the south (Fig. 1c) the park still receives direct sunlight in most of the day except early morning and late afternoon.

2.2. Monitoring sites

The general environmental conditions and fisheye photographs of the selected monitoring sites are shown in Fig. 2. The fisheye images were imported into RayMan 1.2 (http://www.mif.uni-freiburg.de/rayman/intro.htm) to determine the sky view factor of each site. The control site is situated in an exposed lawn (Fig. 2a) with a sky view factor of 0.452 (Fig. 2d). To the northeast of the station is the 3-storey building and a 2.4 m tall green wall (Figs. 1a and 2a). The tree site is 30 m south to the control site (Figs. 1a and 2b). The site is shaded by a Chinese Banyan (*Ficus microcarpa*), a broadleaf evergreen tree native to South China [57], planted on the edge of the large lawn. It is the tallest (9.7 m) and widest tree (crown diameter: 14.0 m) in the park. Its broad crown and dense foliage limit the sky view factor of the site to 0.127 (Fig. 2e). Approximately 25 m west to the control site is the shelter site. It is a naturally ventilated area under the 3-storey building (Fig. 2c). Horizontally it is open to the northwest and the southeast, and vertically it is completely shaded by the concrete ceiling, yielding a sky view factor of 0.004 (Fig. 2f). The non-zero value is due to the reflection of the window façades of the surrounding buildings. The proximity of the three sites allows a valid comparison of their microclimates.

2.3. Meteorological measurements

Five meteorological parameters are measured at each site, namely air temperature (T_a), relative humidity (*RH*), wind speed (v), global solar radiation (G) and black globe temperature (T_g). The specifications and models of the sensors are listed in Table 1. Rainfall was measured at the control site at 2 m. Except for pyranometers which were mounted at 1.5 m, other sensors were installed at 1.1 m, which corresponds to the centre of gravity of adults [38]. Measurements were taken every 10 s. The 1-minute averages were logged by Onset HOBO data loggers (H21-001, Bourne, MA, USA) for T_a, *RH*, v and G, and by Lufft data loggers (Opus 200, Fellbach, Germany) for T_g.

2.4. Measurement period

The mean air temperatures and solar radiation inputs in June, July and August are normally the highest in Hong Kong (Table 2); heat stress reduction is most needed in this period. Measurements were conducted for three consecutive days in each summer month in 2017 (23rd–25th June, 13th–15th July and 5th–7th August).

2.5. Calculation of mean radiant temperature (T_{mrt}), PET and UTCI

PET and UTCI are two widely used outdoor thermal indices [58–61] that allow the integration of all the meteorological parameters (T_a, *RH*, v and T_{mrt}) that affect thermal comfort or stress to a single value [38,62,63]. The final PET/UTCI value corresponds to a thermal sensation or stress level on PET's 9-level scale (see Table 1 in Ref. [10]) or on UTCI's 10-level scale (see Table 3 in Ref. [63]). PET and UTCI were calculated using RayMan 1.2 and BioKlima 2.6 (http://www.igipz.pan.pl/Bioklima-zgik.html), respectively. Among the four required meteorological parameters, only T_a and *RH* could be measured and input into the software programs directly. T_{mrt} and v required further calculation.

The most accurate T_{mrt} determination method involves the 3D measurement of shortwave and longwave radiation fluxes [64], which requires the use of expensive radiometers. The most common alternative is to estimate T_{mrt} by measuring globe temperature [65], which is a more affordable option because of the low-cost of the globe thermometer. In this study, we adopted the latter approach, and T_{mrt} was obtained by the following equation [66]:

$$T_{mrt} = \left[(T_g + 273.15)^4 + \frac{1.1 \times 10^8 v^{0.6}}{\varepsilon D^{0.4}} \times (T_g - T_a) \right]^{1/4} - 273.15 \quad (1)$$

where ε = the globe emissivity (0.95) and D = the globe diameter (150 mm).

PET requires v to be measured at 1.1 m, whilst UTCI requires v to be measured at 10 m. Since wind speed is seldom measured at 1.1 or 10 m, it was suggested that the required wind speed measured at x m (v_x) can be approximated using the log wind profile [63,67]:

$$v_x = v_m \times \frac{\log\left(\frac{x}{z_0}\right)}{\log\left(\frac{m}{z_0}\right)} \quad (2)$$

where v_m = wind speed at measurement height, m = wind speed measurement height (m) and z_0 = 0.01 m for an urban street environment [68].

Apart from environmental parameters, internal heat production and clothing insulation also have to be taken into account in the calculation of PET and UTCI. Internal heat production levels were set at the default values for PET (80 W) and UTCI (135 Wm^{-2}). The default clothing insulation value of 0.9 clo in the RayMan model is adopted, whilst clothing insulation is not a required input in BioKlima 2.6 because it is given by a clothing model [68] that is incorporated into the UTCI-Fiala model [63].