Building and Environment 103 (2016) 262–275

Contents lists available at ScienceDirect

Building and Environment

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

Simulation study on the impact of tree-configuration, planting pattern and wind condition on street-canyon's micro-climate and thermal comfort

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ARTICLE INFO

Article history:
Received 23 February 2016
Received in revised form
21 April 2016
Accepted 22 April 2016
Available online 23 April 2016

Keywords:
Street canyon
Street trees
Tree-configuration
Thermal comfort
ENVI-met
PET

ABSTRACT

Many previous studies have investigated the role of urban greening (especially trees) on thermal comfort condition of open spaces while its influence in street canyons has, however, received relatively lower research attention. In this study, numerical experiments involving street canyons of varying aspect ratio (AR_B) with embedded trees of varying aspect ratio (AR_T), leaf area index (LAI), leaf area density (LAD) distribution and trunk height under different wind conditions were conducted using a micro-meteorological model, ENVI-met. Employing physiological equivalent temperature (PET), the in-canyon thermal comfort was characterized. Results show variable magnitude of PET reduction (ΔPET) with trees of different vertical LAD distribution even though they are of similar LAI. While larger tree-covered area (TCA) ensures improved thermal comfort, the magnitude varies with tree-planting pattern. Between the tree-planting patterns in TCA = 0.6, ΔPET with double-rows is higher than centre tree-planting. Between eastern and western side tree-planting (TCA = 0.3), the former is more temporally effective than the latter. Furthermore, strong oblique wind condition ("without trees") was found to be more efficient in improving thermal comfort than trees under calm perpendicular wind, reinstating the importance of desirable ventilation in achieving a thermally comfortable environment. However, vegetation offers improved PET reduction under calmer perpendicular than stronger oblique wind condition. Finally, recommendations on applications of our key findings were presented.

1. Introduction

1.1. Background of study

Due to global warming and urbanization, global mean surface and air temperature have been projected to increase by 2.6 °C–4.8 C and 2 °C–4 °C, respectively especially in urban areas during this century [1,2]. Moreover, urbanization has resulted in increased density of cities and area of impervious surfaces [3] which are responsible for intensification of anthropogenic/urban heating, carbon dioxide emissions, deforestation (including urban trees) and modification of surface energy balance [4,5]. As a result, temperature extremes and higher frequency/intensity of urban heat stress are prevalent especially during summer season in most tropical countries causing heat stroke and premature death [6–8]. This calls for creation and maintenance of more thermally comfortable indoor and outdoor urban environments. To achieve this, some mitigation and adaptation technical solutions have been suggested: modifications of building and surface materials, alteration of urban morphology, insulation of buildings, installation of irrigation systems and inclusion of urban greenery [9–15]. Among these, addition of greenery in urban area is more advocated and favored means of tackling the current and future global warming and its consequences [15–18]. This is because of its ability to attenuate direct solar insolation thereby reducing surface and air temperature [19–22] and energy demand [23,24]. Variable magnitude of temperature (air and surface) reduction and thermal comfort improvement by trees has been observed depending location of study, greenery density and configuration, prevailing meteorological conditions; and settings of the study site (street canyon or open–environment) [15–18,25–30]. Relatively more

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http://dx.doi.org/10.1016/j.buildenv.2016.04.025
0360-1323/

research has been carried on this subject in an open-environment (such as urban park, residential quarters or institutional environments) than urban street canyon setting.

1.2. Street canyons morphology and thermal comfort

Cities are composed of street canyons of different aspect ratios, orientations and morphologies. Outdoor thermal comfort of such cities is an amalgam of thermal comfort in street canyons. By definition, street canyon is a street bounded by buildings on both sides. The ratio of the building height, H and street width, W is referred to as "Aspect Ratio, AR". Street canyons are classified as symmetrical or asymmetrical if bounding buildings are of equal or unequal heights, respectively [31,32] and can also be categorized based on their orientation i.e. north-south, east-west etc. [33]. To understand the micro-climate and thermal comfort conditions of an individual street canyon, the relationship between its aspect ratio relative to solar angle must be considered. Aspect ratio influences the duration and magnitude of the energy regime of a street canyon [34,35] as depicted in Fig. 1. The amount of energy transfer between the canyon surfaces and overlying air is dependent on surface temperature which is directly determined by the exposure to the sun. With larger area of exposure (in AR = 1), higher surface temperature will be observed and greater radiant energy will be dissipated to the canyon [36,37]. In deep canyons (AR $\geq$ 2) surface temperature is significantly lower due to the shading effect provided by the bounding buildings [37,38]. Because of the interaction between surfaces and overlying air, the air temperature within a street canyon is also affected by the prevalent energy regime. The amount of energy incident in a street canyon is also dependent on its orientation, for example, the duration of exposure is higher in east-west than north-south orientation while other orientation variances show different magnitude and duration of solar access which in turn determine the in-canyon microclimate condition [33,34,39,40]. In terms of geometry, the microclimate evolution in an asymmetrical street canyon which are more representative of real urban morphology [41,42] are believed to be more complex and dynamic than symmetrical canyons [34].

Other previous studies [39,40,43–47] have investigated microclimates, urban heat island intensity and outdoor thermal comfort on symmetrical streets (as in this study) of different orientation and in different climatic zones. Generally, they found that street canyon's aspect ratio influences the thermal condition in street canyon either in hot-humid, hot-dry and Mediterranean climate. Most of the above studies have found inverse influence of deep (AR$\geq$2) and shallow (AR$\leq$1) symmetrical canyon on nighttime heat island intensity and daytime micro-climate improvement i.e. deep symmetrical canyons (AR$\geq$2) increases the nighttime heat island intensity and improves the daytime microclimate and vice-versa for AR$\leq$1 [48–50]. For deep symmetrical canyon, the above described phenomena can be attributed to the air flow stagnation and trapped longwave radiation at nighttime and shading-effect during daytime. For shallow symmetrical canyon, the daytime microclimatic conditions are relatively poor due to the incident direct solar radiation while the nighttime micro-climate improves due to higher outflow potential of stored heat. Based on these previous results, deep and shallow symmetrical canyon are not thermally appropriate as they present conflicting day and night time needs especially in tropical climates [35]. Inclusion of greenery can help dampen this phenomenon by reducing the amount of solar insolation (and consequentially lower magnitude of heat storage) to the street canyon but could also lower wind speed

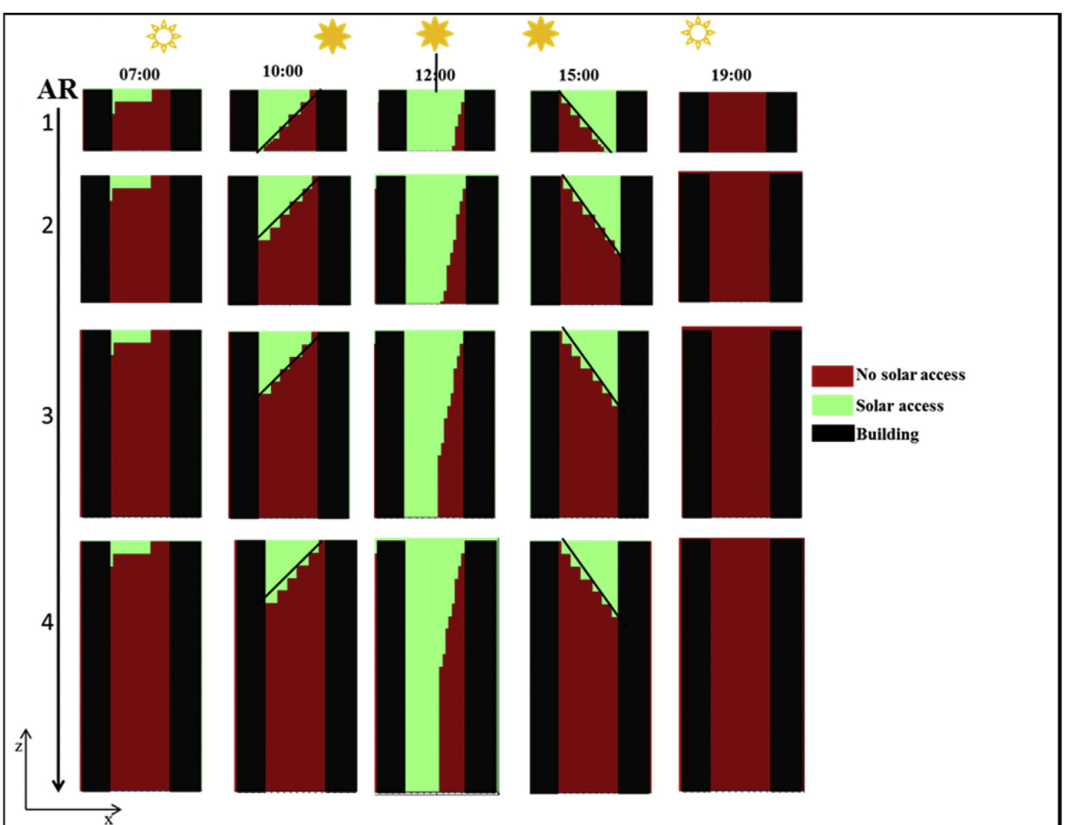

Fig. 1. Evolution and distribution of solar access inside street canyon of different aspect ratio.