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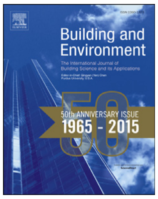

A new method to assess spatial variations of outdoor thermal comfort: Onsite monitoring results and implications for precinct planning

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ABSTRACT

Residents wish to have outdoor spaces to enjoy walking, cycling, and other recreational activities, which are often hindered by the unfavorable thermal comfort conditions, especially in the summer. High building densities lower the average wind speed and this intensifies the urban heat island effects at city scale. The conscientious use of building morphology to create local thermal comfort zone at selected spots in a large precinct is becoming a pressing issue for sustainable urbanization. This paper is a proof of concept study via continuous monitoring of the pedestrian level winds and thermal parameters at two sample days in summer, which include instantaneous air temperature, globe temperature, wind speed and humidity. Three outdoor locations at an university campus are chosen and daytime thermal perceptions at the three sites were evaluated using PET (Physiological equivalent temperature). A PET based new index was defined, which is called the thermally-perceivable environmental parameter difference. By analyzing the simultaneous differences of radiant temperature, wind speed and air temperature between the monitored spots, it is shown that it was the wind speed and radiant temperature differences that were making significant differences in thermal comfort. This pilot study clearly indicates that wind amplification combined with shading effects can generate thermally comfortable conditions in the open ground floor beneath an elevated building, even on a sunny, hot summer day in a subtropical city. This finding helps to alert city planners of additional options available in precinct planning to encourage outdoor activities.

1. Introduction

City residents normally spend much time indoors without enjoying the outside natural wind and sunshine. Statistical surveys report that outdoor recreational activities such as walking and cycling benefit both physiological and psychological health [1,2]. Meanwhile, more time spent outdoors effectively reduces the building energy consumption for air conditioning and artificial lighting, especially in hot and humid regions. Gehl [3] proposed that public spaces should be made more livable for the citizens and his study revealed that sensitive bench positioning in relation to sun and shade had an impact on the popularity of a public space. In recent decades, more and more researchers have considered designing outdoor places to be more attractive to citizens and proposing this a goal for urban planning and building design [4–6].

The outdoor built environment (created by the arrangements of building clusters) has modified the surrounding microclimate in a city. For the urban scale (10 km–100 km) [7], the urban heat island (UHI) effects are well known, and the establishment of better microclimates for residents is now a great challenge [8]. Li et al. [9] proposed the concept of city ventilation and showed the analysis that the thermally driven flows and building surfaces flows can remove airborne pollutants and the exhaust heat released from the buildings in a high-rise dense city. The Air ventilation assessment (AVA) scheme of the Hong Kong SAR government [10] serves as a

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policy and technical guideline [11] for urban planning and building design. The core recommendation in this AVA guideline is to amplify pedestrian level wind in Hong Kong. Givoni et al. [5,12] proposed that urban wind amplification can be obtained by appropriate arrangements of high-rise and low-rise building blocks. The height differences create complicated wind flow patterns around buildings to arouse different wind speeds at different local areas such as the “street canyon” formed between buildings. For hot climates, wind is very much desirable for summer comfort.

During past decades, many researchers have investigated urban scale bio-meteorology and city climatology for the purpose of outdoor thermal comfort evaluation for different climatic zones of the world [13–17]. Most of these studies employed field measurements and survey of outdoor thermal parameters and human behaviors in urban districts [14,18–21]. A few researchers evaluated outdoor thermal comfort by numerical simulations [22–24].

The choice of a bio-meteorology index for outdoor thermal assessment has been a special research topic. The indices were mainly divided into two types based on their assumptions, empirical studies and the heat budget model of human body. Nagano and Horikoshi [25] summarized these indices and presented their availabilities for different problems. The OUT_SET* [26,27] transferred from the standard effective temperature (SET*) of indoor version [23] for the outdoor use by simplifying the complicated radiation environment into “standard” environment was an empirical index. The other indices which were obtained based on physiologically modeled relationships were the PMV (Predicted Mean Vote) model by Fanger (1972) [28] and the PMV* model further developed for outdoor use by Gagge et al.(1986) [29]. Another typical and frequently used index, physiological equivalent temperature (PET), was introduced by Höppe [30] for outdoor thermal comfort evaluation, which was based on the Munich energy-balance model for individuals (MEMI), and *PET* for different grades of thermal perception in Western and Middle Europe had been presented. Meanwhile, Lin and Matzarakis [31] reported different PETs value for the neutral condition in subtropical Taiwan region, based on the climatic data analysis and tourists' surveying results (Table 1). It is shown that people in Taiwan were more sensitive to the thermal environmental parameter changes. In addition, UTCI (Universal thermal climate index), which was proposed more recently, was a more complex heat budget based approach and was increasingly used by bio-meteorological researchers [32,33]. Other methods for assessing human thermal responses to local thermal environment are the Index of thermal stress (ITS) [12]and the COMFA outdoor thermal comfort model [34].

Table 1
PMV and *PET* for different grades of thermal perception and physiological stress on human beings in Taiwan and Western/Middle European ranges [31,35].

PMV	PET range for Taiwan (°C)	PET range for Western/Middle European (°C)	Thermal perception	Grade of physiological stress
			Very cold	Extreme cold stress
−3.5	14	4		
			Cold	Strong cold stress
−2.5	18	8		
			Cool	Moderate cold stress
−1.5	22	13		
			Slightly cool	Slight cold stress
−0.5	26	18		
			Comfortable(Neutral)	No thermal stress
0.5	30	23		
			Slightly warm	Slight heat stress
1.5	34	29		
			Warm	Moderate heat stress
2.5	38	35		
			Hot	Strong heat stress
3.5	42	41		
			Very hot	Extreme heat stress

Field measurement has been the main method used for evaluating the micro-climate and outdoor thermal comfort, as reported by Nikolopoulou et al. [13,14] and Mayer et al. [36] for Western European country comparisons, Ali-Toudert et al. [16] and Johansson [18] for hot dry climates, Lin et al. [15,37] and Johansson et al. [19] for hot and humid climates, and Bauche et al. [31] for a cold climate where PET was lower than 0 in a Russian city. Some previous Asian urban micro-climate researchers were also very active, for instance, Ng et al. [11] investigated urban human thermal comfort in Hong Kong, Lin and Hwang [37,38] in Taiwan, Thorsson et al. [21] and Knez et al. [39] investigated Japanese urban public places, Jeong et al. [40] conducted similar studies in Korea; and for Mainland China, there were related investigations in Nanjing [41], Wuhan [42,43] and Tianjin [44].

Studies on a few typical outdoor spaces, which were known to have their own micro-climate, have been reported. Lin [15] investigated the thermal relationship between perception and numbers of people in a public square. Ail-Toudert et al. [45,46] and Hwang et al. [47] investigated the impact of canyon orientations and vegetative shading in street canyons. Some semi-outdoor environments such as a railway station, municipal cultural center, art center and museums have been investigated by Hwang et al. [48] and Zhou et al. [42], and it was suggested that shading design improves outdoor thermal comfort by shielding the solar radiation. Measurements in a public park [38,39,49,50] revealed that shading level affects the number of visitors, because of better thermal comfort, in the resting places. In addition, shading provided by trees and buildings in a large, open campus [20,51] was found to significantly improve thermal comfort in summer.

Reviewing these studies on how built environment design can significantly modify the local, also called micro-environmental, wind and thermal comfort conditions by means of wind amplification/attenuation and solar radiation/shading effects, a hypothesis is established that, although high building densities lower the average wind speed and intensifies the urban heat island (UHI) effects at city scale, the conscientious use of building morphology to create local thermal comfort zone at selected spots in a large precinct is very possible. Specifically, for hot and humid climates, shading is desirable; the downwash from a high-rise building can be ‘funneled’ to the intended spots. This hypothesis is based upon the authors' observations of some landmark building designs. One example is shown in Fig. 1 – the open ground floor formed beneath the elevated building blocks in our university campus. It is proposed that creating such thermally comfortable spots in a precinct via the integration of several architectural features could become a design objective in urban and community planning, be significant for public health, enhancing perceived livability of a city, and fulfilling the aims of sustainable urbanization. The objective of this paper is to reveal the local differences in thermal perceptions that exist in practice, via simultaneous onsite monitoring of environmental parameters at the pedestrian level at three selected sites in a precinct. This study serves as a proof of concept or performance testing study.

2. Methodology

2.1. On-site monitoring

The architectural layout of an existing campus is taken as a prototype design, and three different sites at the campus have been chosen as the testing samples. The thermal environmental parameters that are known to affect the thermal comfort of pedestrians were monitored continuously for two sample days at these