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Urban form and density as indicators for summertime outdoor ventilation potential: A case study on high-rise housing in Shanghai

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ABSTRACT

Pedestrian-friendly wind environment is an important target of urban design. For emerging mega-cities in the sub-tropical climate, design effort should be made to optimize ventilation potential at outdoor spaces during the hot-humid summer months. This study aimed to examine the micro-scale effect of urban form and density (of building and/or greenery) on outdoor ventilation potential, using empirical data from an extensive field measurement. The selected ten high-rise residential sites in inner-city Shanghai were grouped in four urban climate zones (UCZ) based on urban cover and urban structure, in order to control the local-scale urban influence on the measured micro-scale wind parameters for the sites in each UCZ. The wind statistics indicates significant influence from surrounding urban geometry. A simple scatter plot and linear-fit analysis indicates that, the pedestrian-level WVR is significantly correlated with the "degree of enclosure" contributed by buildings and/or greenery, quantified by the sky view factor (SVF), tree view factor (TVF) and green plot ratio (GPR). It suggests that within the practical range, increasing SVF by 10% could increase WVR by 7–8%. Under the observed weak wind environment, SVF could indicate the thermal buoyancy driven airflow rate that is determined by solar radiation heating. A discussion on the observed weak wind environment suggests an urban design approach that goes for a "diverse" instead of a "uniform" wind environment which supports various users and activities.

1. Introduction

Enhancing city ventilation in summertime is important for human thermal comfort, building cooling energy saving and pollutant dispersion [1]. However, in densely-populated cities, the pedestrian-level air movement is overall heavily compromised due to the frictional drag imposed by urban surfaces. The degree of the frictional drag depends on the roughness of the surface(Ref. [2], p.54). In areas such as city center, the roughness length (z_0) can be 8–10 times that of its suburb/rural surroundings [3]. According to theory, the zero-plane displacement (d) in high-rise high-density cities can be remarkably higher than the ground surface, indicating that in deep street canyons, the pedestrian-level airflow can be caused largely by turbulence. Therefore, the overall velocity is lowered, but the distribution is highly varied both spatially and temporally, depending upon the prevailing wind profile and surrounding urban geometry [4]. The wind effect of tall building differs in different climates. For instance, in cold/temperate climates, the downward airflow deflected by tall buildings can cause strong and unfavorable pedestrian winds and need proper mitigation measures, whereas in hot-humid climates, this is an important channel to enhance street ventilation [5]. It is possible to modify urban air movement by manipulating city morphology, urban form and street geometry [6]. Therefore, for urban designers, the complex urban winds and its interplay with urban form poses critical challenges, and offers great opportunities as well, in creating a properly ventilated, pedestrian-friendly urban space.

Studies focusing on building-induced strong wind and its impact on pedestrian wind comfort have been carried out in developed countries in cold/temperate climates. Bottema summarized the effect of wind on people base on the Beaufort scale [7]; Lawson defined unacceptable and tolerable thresholds of occurrence of strong winds based on six activity/usage categories [8]. But not many studies have focused on the summertime weak winds in emerging mega-cities in developing countries. In particular, empirical data is scarce.

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Shanghai (latitude 31.23°N and longitude 121.47°E) is located on the east coast of China, in the sub-tropical climate zone that subjects to strong monsoon influence. The summer is hot and humid. The Observatory data indicates that, the monthly-average of daily-mean air temperatures in July and August can reach 28 °C, and the monthly-average of daily-maximum air temperature can reach as high as 32 °C. A major portion of the annual precipitation occurs in the period from June to September. The mean wind velocity (WV) in the urbanized area have continuously decreased ever since the 1880s [9]. Since the rural wind observatory was set up in the 1950s, the urban–rural WV difference have been continuously observed, in the order of 0.5–1.3 m/s, and the trend was negatively correlated with urbanization process, indicated by the ever-increasing residential building coverage in urban areas [9]. The summertime mean WV recorded at the urban observatory is 3.4–3.9 m/s [10]. The pedestrian level WV is estimated as roughly 70% of the standard meteorological measurement, i.e., at 10 m a.g.l. centered in an open terrain [11]. In dense urban areas, it is reasonable to anticipate a further reduced WV at the pedestrian level. Thus, to improve summertime outdoor comfort, the priority of design consideration should be increasing winds to velocities conducive to positive cooling effects.

This study intends to investigate the summertime winds at the pedestrian level in high-rise residential quarters in the inner-city of Shanghai, using data collected from an extensive field measurement. It tries to gain an in-depth understanding on the wind pattern under typical summer weather conditions, and to quantify the effect of built-form and greenery variables on the pedestrian-level ventilation potential.

2. Background

The pedestrian-level wind pattern is influenced by ambient wind and urban geometry. Analyzing the wind effect of urban buildings is facilitated by parameterizing the canyon geometry, e.g. by the aspect ratio (H/W, ratio of mean building height to street width) of urban canyons. Oke summarized three distinct airflow regimes associated with H/W of urban canyon geometry, i.e., isolated roughness flow, wake interference flow and skimming flow [12]. Field measurements have been carried out to understand and evaluate the airflow pattern in typical canyon geometries in European cities, e.g. Refs. [13,14]. While the aspect ratio may well describe those traditional cities where the historic fabric is well preserved, it can be difficult to apply in emerging Asian cities, where rapid urbanization has created a juxtaposition of high-rise new developments and low- and mid-rise old buildings. A consistent and continuous streetscape is difficult to find, and the resultant pedestrian wind pattern is complicated and difficult to analyze according to the classic three-stage wind regimes. Instead, parameters derived from 3-dimensional urban analysis could be more useful, for instance, sky view factor (SVF), floor area ratio (FAR), building coverage ratio (BCR), frontal area index (FAI), etc [12].

Theoretically, to enhance the pedestrian-level airflow within the urban canopy layer (UCL), the production of turbulence should be enhanced above the roof level, i.e., in the urban boundary layer (UBL) [12]. Research has revealed that, within the range of 0.13–0.32, increase in BCR firstly tends to increase the turbulence production but then decrease when it exceeds around 0.25 [12]. Given the same BCR, a mixed-height tall building cluster can create stronger turbulence than a homogeneous low-rise village [4]. A wind-tunnel study has found that, given the same range of BCR, the wind velocity ratio (WVR) in high-FAR building sites (i.e., high-rise apartment buildings) is markedly higher than in low-FAR building sites (i.e., low-rise detached houses) [15]. A numerical study on Guangzhou, China investigated a number of site planning scenarios, with a fixed BCR of 0.4 but varied FAR values ranging from 0.8 to 7.6. It is found that the mean WV firstly increases with FAR and then decreases; the mean WV reaching the highest and the thermal comfort the optimum when FAR = 5.6 [16]. This finding suggests that for a given BCR, an optimum building volume and layout may exist in terms of maximizing on-site ventilation potential.

Tree canopy is generally considered beneficial for reducing summertime air and surface temperature by shading and evaporative cooling, but it can also reduce the ventilation potential underneath the canopy. This is easy to comprehend: Consider the wind profiles under two distinct ambient wind directions in a deep urban canyon (H/W > 2) with trees. The in-canyon airflow is either driven by the downward vortex in opposite direction, under a ambient wind perpendicular to the canyon axis, or the along-canyon flow with a downward incidence angle of 0°–30° relative to the canyon floor, under a ambient wind parallel to the canyon axis [17]. In both scenarios, the tree canopies tend towards present a barrier to air circulation at the pedestrian level. In other words, in addition to solar heat, trees may unfavorably block the airflow. From the thermal comfort perspective, the landscape design should therefore optimize the composition of various vegetation patterns (i.e., grass, shrubs, trees, etc.) [18].

The above analyses indicate that, the degree of openness (to the sky) can be a useful indicator of ventilation potential, in that the “degree of enclosure” created by building and/or vegetation canopy can be related to the probability of air stagnation. SVF has been correlated negatively with the maximum urban heat island intensity and positively with the diurnal temperature fluctuations, as it indicates the capability of daytime short-wave heating and nighttime long-wave cooling at ground horizontal surfaces [19,20]. But no research has been found in correlating SVF with street ventilation performance. This study attempts to extend its application in the street airflow evaluation. SVF and other two variables, i.e., tree view factor (TVF) and green plot ratio (GPR) will be measured and used as indicators of building and vegetation density, to evaluate the effect of urban canopy (buildings and/or greenery) on the pedestrian WVR. SVF and TVF are defined as the fractions of the overlying hemisphere as shown in a sky view image that are occupied by the sky and by vegetation canopy, respectively [21]. GPR is developed by Ong from leaf area index (LAI), to measure the leave density of a site instead of a single plant [22], it is defined in this study as the ratio of total leaf area to the 20 m-radius area centered by the point under measurement.

Efforts have been made to develop standardized tools and protocols for specific Asian high-density cities, to assess the pedestrian wind effect of existing or proposed urban developments. Two examples of such tools are the air ventilation assessment (AVA) system from Hong Kong China, which uses physical wind tunnel to evaluate the ventilation impact of a new development on the site as well as its surrounding urban areas [5]; and the guidelines proposed for practical applications of computational fluid dynamics (CFD) technique in predicting the pedestrian-level urban wind environment in Japan [23]. To apply the tools alike to the city of Shanghai, some key issues may need better understanding: What are the real-world wind patterns in typical high-rise developments? What are the wind effects of urban-form factors at the urban, local and micro scales? To what extent can we improve the site ventilation by manipulating the micro-scale building form and greenery variables? Studies based on empirical data should be useful. Empirical modeling can be supportive to future parametric studies, in setting up appropriate design targets, benchmarks, and model boundary conditions.