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Pedestrian-level wind environment around isolated buildings under the influence of twisted wind flows

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ABSTRACT

The influence of twisted wind flows on pedestrian-level wind environments was evaluated by using two twisted wind profiles (TWP) in a boundary layer wind tunnel. Simulated wind profiles had maximum yaw angles of 13° and 22° to represent 'high' and 'extreme' wind twist conditions, respectively. Five buildings with the aspect ratio (Height: Width) of 4:1 to 0.5:1 were tested for a number of wind incidence angles to assess the influences of building dimensions and approaching wind directions. All test cases were repeated in a conventional wind profile (CWP) with similar mean wind speeds and turbulence intensities for the purpose of comparison. The results reveal that pedestrian-level wind environments in TWPs are different than in CWPs owe to asymmetric wind fields, displaced flow features, and variations in areas of high and low wind speeds. The increased areas of low wind speeds and displaced downstream far-field low wind speed (DFLWS) zone are the two important flow modifications that would have negative impacts on outdoor thermal comfort and air pollutant dispersion in built-up areas where TWPs exist. Due to the embedded wind twist angles, wind incidence angles have different effects on flow modifications in twisted wind profiles than in conventional wind profiles.

1. Introduction

Wind conditions in a neighbourhood directly influence the urban environment through impacting air pollution dispersions (Mage et al., 1996; Fernando et al., 2001), outdoor thermal comfort (Stathopoulos, 2006; Mochida and Lun, 2008), and pedestrian-level wind nuisance (Isyumov and Davenport, 1975; Blocken and Carmeliet, 2004). Particularly, the near-ground wind environment is an important factor in determining the livability of a built environment. Since the beginning of tall buildings being constructed in cities, wind has been a nuisance to pedestrians because tall buildings bring high-speed winds from higher altitudes to the ground level and generate unpleasant or even dangerous high wind speed areas around building corners (Melbourne and Joubert, 1971; Murakami et al., 1979; Kamei and Maruta, 1979). Unacceptable windy areas became a critical issue in cities and thus a number of guidelines on wind environments have established criteria for pedestrian comfort to encourage better urban planning and to advice on preventive measures. (Penwarden, 1973; Bottema, 1999; Koss, 2006). Ironically, however, over the last few decades, pedestrian-level wind nuisance in cities such as in Hong Kong, Milan, Delhi and Tokyo has transformed from unpleasant high wind speed to undesirable low wind speed (Tsang et al., 2012; Vignati et al., 1996; Goyal and Siddhartha, 2002; Chetwittayachan et al., 2002). These low wind speeds are likely the result of excessive wind blockage of closely-spaced tall buildings; where buildings act as a wall against approaching wind flows. This phenomenon, generally referred to as the "wall effect of buildings", is frequently observed in building developments at waterfront areas in Hong Kong (Yim, Fung, Lau and Kot, 2009). As a result of intercepted wind flows, wind speeds at the street level are below par the requirement of 1.5 m s^{-1} in Hong Kong and tend to swell poorly ventilated urban areas with higher levels of air pollution (Wang and Lu, 2006). Furthermore, substandard city ventilation in Hong Kong ultimately may lead to an epidemic such as the outbreak of SARS in 2003, which caused nearly 300 deaths (Yu et al., 2004).

Proper urban planning is key to maintaining tolerable wind conditions in cities (Arnes, 1981; Ng, 2009). Therefore, many municipal authorities have established guidelines for preserving acceptable wind speeds for different types of activities such as walking, sitting and leisure activities (Melbourne, 1978; Arnes, 1989; Durgin, 1989). For example, the Air Ventilation Assessment (AVA) implemented by the Hong Kong Government states its main objective as to maintain an

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adequate level of ventilation at the pedestrian level in urban areas through assessing the impact of new developments to the existing wind environment (Ng et al., 2004). The AVA combines data of approaching wind profiles at the project site obtained via a topographical wind tunnel test and calculated probability of occurrence of winds from the probabilistic wind climate model of Hong Kong with the measured pedestrian-level wind speeds from a detailed AVA wind tunnel study to assess if the proposed development would impede the accepted minimum mean wind speed of 1.5 m s^{-1} at the pedestrian-level (Ng, 2009). Evidently, the reliability of AVA results substantially relies on the accuracy of extracted meteorological wind data and simulated and measured wind conditions in wind tunnel tests. However, topography-induced twisted wind flows in Hong Kong, whose existence was confirmed by studies of Weerasuriya et al. (2016), Li et al. (2016), and Tse et al., (2016), introduce uncertainties to both the wind tunnel measurements and the way they combine with meteorological wind data.

In several ways, these twisted wind profiles are different from conventional wind profiles that are used for general wind tunnel tests including the AVA wind tunnel study. A twisted wind profile has different wind directions along the profile's height as opposed to a constant wind direction, which is associable with conventional wind profiles. It is noteworthy that the direction of atmospheric wind flows is naturally varied in the vertical direction at the scale of the atmospheric boundary layer height due to the combined effects of the earth's rotation, surface friction, and pressure gradient force. The varying wind directions create a spiral-shaped wind profile, which is commonly known as the Ekman Spiral (Dyrbye and Hansen, 1996). Besides aforementioned force effects, some local factors such as the change of terrains, and different atmospheric stabilities can also contribute to generating twisted wind profiles (Peña et al., 2014). However, complex and hilly terrain, in general, is believed to be the main cause of twisted wind profiles observed in Hong Kong (Tse et al., 2016). These topography-induced twisted wind profiles are characterized by larger yaw angles (about 40°) and are confined to the lower 500 m of the atmospheric boundary layer (Tse et al., 2016). These twisted wind profiles observed to have significant wind direction changes over relatively low altitudes may substantially influence the 'habitat' layer, where people live and structures are located. From the AVA point of view, the non-deterministic nature of wind direction of twisted wind profiles induces uncertainties in determining the probability of occurrence of winds in a given wind direction. Moreover, the use of conventional wind profiles (typical simulation of ABL wind flows with a constant wind direction) for wind tunnel tests in the AVA is an ill-representation of field conditions, where twisted wind profiles actually exist. It is noteworthy that the non-deterministic nature of the wind direction of a twisted wind profile can be partially rectified by using statistical methods in post analysis of AVA. The effect of twisted wind flows on the pedestrian-level wind environment, however, has not reflected in typical wind tunnel tests that employ conventional wind profiles. According to the authors' best knowledge, no previous pedestrian-level wind tunnel tests have employed twisted wind profiles as a boundary condition. Therefore, the main focuses of this study are to incorporate twisted wind profiles for pedestrian-level wind tunnel tests and to systematically evaluate the influence of twisted winds on wind conditions near ground level.

Pedestrian-level wind environment in a built-up area is a blend of numerous flow fields resulted from interactions of approaching winds and surrounding buildings. Due to the complexity of interacting flow fields in built-up areas, researchers have employed some basic building configurations such as isolated buildings or building clusters to represent real urban areas in wind tunnel tests. Isolated buildings are the simplest building form used in fundamental wind tunnel studies due to its (1) ability to generate less complex flow conditions than if many buildings are involved, and (2) capability of producing all important flow features in the surrounding wind environment (Beranek, 1984; Hosker, 1985; Lam, 1992). Therefore, isolated building models are used in this study to elucidate any alternation induced by twisted wind flows to the surrounding wind environment. However, the flow field around an isolated building does not merely depend on properties of an approaching wind but is also associated with building dimensions and wind incidence angles (Beranek, 1984; Bottema, 1993; Wu, 1994; Tsang et al., 2012). Hence, the current study focuses on assessing the combined effects of twisted wind flows, building dimensions, and wind incidence angles on the pedestrian-level wind environment in a built-up area.

Following the introduction, the experimental setup is presented in Section 2 with details of the simulation of twisted wind profiles and their flow properties. Details of building models and techniques employed to measure wind speeds are also illustrated in Section 2. Section 3 demonstrates results of mean wind speed measurements at the pedestrian level. The first half of Section 3 presents variations of discrete wind speeds measured along the longitudinal and lateral wind directions near buildings. The qualitative and quantitative analyses of pedestrian-level wind speeds with respect to building dimensions and wind incidence angles are illustrated in the second half of Section 3. Concluding remarks of the study are presented in Section 4.

2. Experimental setup

2.1. Simulation of twisted wind flows

Twisted wind flows described in this paper were simulated in the 'low-speed' section of the CLP Power Wind/Wave Tunnel Facility (WWTF) at the Hong Kong University of Science and Technology (HKUST). This wind tunnel is a closed-circuit type boundary layer wind tunnel (BLWT) with two parallel test sections named as the 'high-speed' and 'low-speed' according to their ranges of operating wind speeds. The low-speed section is the largest test Section (5 mx4 m) but has a smaller maximum operating wind speed of 10 m s^{-1} at a height of 1 m. Since the large dimension of the low-speed section provides sufficient room for the simulation of the twisted wind flow, all wind tunnel tests in this study were completed in there using the maximum operating wind speed.

Twisted wind flows were simulated using custom-designed wooden vanes as shown in Fig. 1. All vanes were 1.5 m tall and were manufactured using laminated wooden strips with desired profiles of guide angle at their trailing edge. The profile of guide angle followed an exponential function with height such that the yaw angle reached the maximum value at the ground level and reduced to 0° at 1 m height. The rest of the 0.5 m height contained a straight wooden board to minimize any unwanted eddies generated from the edges of vanes that may reach the measurement area. Two sets of vanes with maximum guide angles of 15° and 30° were employed to represent 'high' and

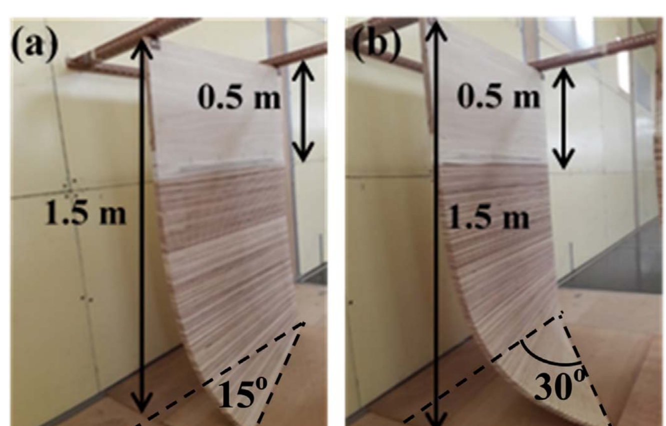

Fig. 1. Two wooden vane systems with maximum guide angles of (a) 15°, and (b) 30°.