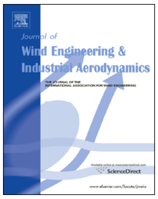
J. Wind Eng. Ind. Aerodyn. 137 (2015) 14–24

Contents lists available at ScienceDirect

Journal of Wind Engineering and Industrial Aerodynamics

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



Surface wind pressure tests on buildings with various non-uniformity morphological parameters

Biao Li [a], Jing Liu [a,b,*], Jiaming Gao [c]

[a] School of Municipal and Environmental Engineering, Harbin Institute of Technology, Harbin, China
[b] State Key Laboratory of Urban Water Resource and Environment, Harbin Institute of Technology, Harbin, China
[c] Shenzhen Institute of Building Research Co., Ltd, Shenzhen, China

ARTICLE INFO

Article history:
Received 20 June 2014
Received in revised form
13 November 2014
Accepted 18 November 2014

Keywords:
Non-uniform buildings
Wind pressure
Drag coefficient
Wind tunnels
Morphological parameters

ABSTRACT

The wind environments in real urban areas, which consist of various significantly non-uniform buildings, are completely different from those in regular building arrays or homogeneous underlying surface areas. Through boundary layer wind tunnel experimental studies, the present work aimed to investigate the possible effects of non-uniformity morphological parameters of buildings on the drag coefficient, with consideration given to the non-uniformity of the frontal area, density, shape, and layout of buildings. And a novel non-intrusive approach to drag measurement, based on wind pressure tests performed on three single buildings, was developed and compared with the direct measurement method. The experimental analyses indicate that among different cases, in general, the variation tendency of the drag coefficient of individual blocks positioned along a wind direction over a large planar area was approximated as an attenuation curve. Moreover, the drag coefficient results from the wind pressure tests vary by 10–20% from those based on direct measurements. Furthermore, when the layout was a diagonal-square network, which is considered for buildings that have better ventilation conditions, it was observed that the wind pressure difference coefficient of those pressure modules would increase. There are clear differences between an H-shaped building and a rectangular one, such as their distributions of the wind pressure difference coefficient and the fact that the H-shaped structure induces flow more intensely. In addition, the effect of changes in terrain roughness on the distribution of the surface wind pressure difference coefficient is not significant.

1. Introduction

Wind undergoes a significant decrease in velocity when it flows over buildings, especially in urban areas, which is clearly different from the behavior observed for the homogeneous underlying surface (Roth, 2000; Perry et al., 1987). In fact, the underlying surface of urban buildings is non-uniform, with the roughness extremely difficult to estimate because of its complex structure and the unique geometry of various buildings. Kanda et al. (2013) indicated that the real urban surfaces present essential difference in bulk flow properties from those in simplified arrays, based on a large-eddy simulation (LES) database including both real urban areas and simple arrays. The non-uniformity of underlying urban surfaces is the primary cause of the urban climate (Arnfield, 2003; Pielke et al., 2002) because it directly results in a large, uneven exchange of energy, momentum and material in the atmosphere within a given area. In considering the effects of non-uniform buildings on aerodynamic characteristics, various types of field measurements (Tran et al., 2006) and model experiments (Hagishima et al., 2009; Cheng et al., 2007; Han et al., 2005) have been used to study the effects of urban areas on the atmosphere, the latter of which are usually conducted in atmospheric boundary layer wind tunnels. Moreover, early researchers studied the dependence of drag on geometry, mainly in the area of micro-meteorology (Lettau, 1969, 1967) or vegetation (Wooding et al., 1973; O'loughlin and Annambhotla, 1969; O'loughlin, 1965). Over the span of nearly 20 years, increasing attention has been given to the effects of urban underlying surfaces on the atmospheric boundary layer, where buildings play a significant role.

Perry et al. (1969) indicated that the total drag coefficient C_d of a rough wall is due to both frictional drag and form drag, whereas the latter is assumed to be dominant for urban surfaces, which depend predominantly on the geometry of the underlying rough surface. Leonardi and Castro (2010) recently addressed the partition of drag force, using direct numerical simulations with staggered arrays of cubes in terms of various plane area densities. Their results showed that the surface drag is predominantly form drag while the frictional component of total drag is less than 7% in

---

[*] Correspondence to: School of Municipal and Environmental Engineering, Harbin Institute of Technology, Nangang District, PO Box 2651, Harbin 150090, China. Tel.: +86 451 86282123; fax: +86 451 86282123.
E-mail address: liujinghit0@163.com (J. Liu).

http://dx.doi.org/10.1016/j.jweia.2014.11.015
0167-6105/© 2014 Elsevier Ltd. All rights reserved.

most cases. To accurately determine the aerodynamic characteristics of an urban area, aerodynamic parameters such as the drag exerted on an urban surface by fully developed turbulent flow were the primary subject of experimental studies in both field measurements and laboratory measurements. There have been notably few field measurements because it is too difficult to identify reasonable experimental objects due to the complex characteristics of a real urban area. Wang (1992) conducted an observational experiment in Lanzhou, considering the complex, surrounding urban area and the effects of vertical and lateral wind components on building structures; the study indicated that the intensity of the lateral wind component's turbulence on the urban surface layer in Lanzhou is 20% greater than that on the homogeneous underlying surface in urban areas. Rotach (1993) measured turbulent wind and temperature fluctuations in the vicinity of the roof level within the urban roughness sublayer, discussed the non-dimensional gradients of wind speed and temperature within a roughness sublayer. In contrast, precise and controllable wind tunnel tests have helped deepen the understanding of the nature of air flow. Thus, laboratory measurements have become the dominant methods for determining the effects of urban underlying surfaces on aerodynamic characteristics. Considering the non-uniformity of an urban surface model, most surfaces can be divided into two groups: non-uniform urban surfaces (Zaki et al., 2011; Cheng and Castro, 2002; Wooding et al., 1973), and regular arrays (Hagishima et al., 2009; Coceal et al., 2007; Kanda and Moriizumi, 2009; Raupach et al., 1980; Wooding et al., 1973).

With respect to laboratory measurements, many researchers have sought to better understand the effects drag forces on urban areas; the use of drag measurements and, to the best of our knowledge, direct measurements of drag forces in an urban area have only been conducted in wind tunnel experiments. Iyengar and Farell (2001), using a floating-element force balance (with a measurement uncertainty of less than 2%) in a wind tunnel, measured the wall shear stress in the atmospheric boundary layer. Cheng et al. (2007) developed a wind tunnel experiment to investigate the effects of two uniform, urban-type surfaces with different area densities, in which a floating drag balance and pressure tapping were used. The floating raft was specially located in an oil base to prevent air leakage and to produce theoretically zero internal friction. Hagishima et al. (2009) conducted a wind tunnel experiment to investigate the aerodynamic effects of various configurations of urban arrays; the authors also designed a floating element to directly measure the total drag and showed uncertainties of less than 0.2% in five repeated measurements for each case. Zaki et al. (2011) performed wind tunnel tests to investigate the effects of urban arrays exhibiting 'vertical' or 'horizontal' randomness; the authors used the same set-up employed by Hagishima et al. (2009) to measure the total drag. Li et al. (2013) designed a floating experimental platform to study the effect of non-uniform buildings on drag, and the platform was completely floated on a flume bath to improve the accuracy of their measurements.

To determine the drag of an urban area, as in all of the above mentioned studies, the use of an accurate and simple set-up or method of measurement is highly important. In most studies reported in the literature, researchers have designed floating set-ups to satisfy the demands of drag measurements, and nearly all of them have used balance facilities, which are primarily composed of mechanical elements and stress or force sensors. The uncertainties in the measurements performed using some of these methods were determined by repeated experiments, but this uncertainty was not directly associated with the total precision of the drag; in other words, the uncertainty was more indicative of the repeatability of the set-up, rather than the total accuracy of the drag measured. The accuracy of drag measurements is mainly determined by the measurement accuracy of the mechanical elements and sensors of a given experimental set-up, the resistance of the floating element, and the error in the airflow for the presence of the set-up. The first two factors are easy to understand, but the last one is not as obvious. This factor is similar to flow over a floating plane ground with an experimental set-up that is different from the ground of an urban area, which is stable in terms of properties such as rotation, incline, and vibration under turbulent flow, let alone some intrusive experimental set-ups. Indeed, all of the aforementioned factors will lead to higher uncertainty and lower accuracy. In particular, direct measurement methods are infeasible for performing drag measurements for real urban areas, thus restricting further field or full-scale studies on real urban areas.

Conversely, wind pressure tests afforded by rigidity models are considered to be a useful and precise method for obtaining the surface pressure of buildings in wind tunnel tests. While direct force balance measurements are usually the preferred method for drag measurements, pressure measurements are widely used when information on the distribution of surface pressure is desired. The wind pressure on the surfaces of blocks can be measured directly using a scanning valve system without other mechanical elements or facilities and can be more accurate than other measurement methods. This method has been well applied in measurements of building structures, such as the measurement of the wind load on a building structure or wind interference on buildings (Cermak, 2003; Tieleman, 2003; Khanduri et al., 1998; Dyrbye and Hansen, 1996). The method has also been adapted to acquire the wind load of a wind turbine for the purposes of rotor design and load calculations (Joselin herbert et al., 2007; Snel, 2003; Hansen and Butterfield, 1993). In addition, several researchers have used wind pressure methods to study the effects of buildings on indoor or outdoor airflow (Costola et al., 2009; Ahmad et al., 2005). Hussain and Lee (1980) studied the surface pressure field of low-rise buildings using a series of wind tunnel tests for different isolated building shapes, building forms, and array forms. Chand et al. (1998) used a pressure-measuring system to determine the mean wind pressure distribution on the opposite wall of a five-story building, with or without balconies on it, and studied the effect of balconies on ventilation-inducing wind forces in a low-speed wind tunnel; Montazeri and Blocken (2012) validated this wind tunnel experiment using Computational Fluid Dynamics (CFD) and indicated that the pressure distribution on building surfaces is important for the evaluation of wind loads and natural ventilation. Kim et al. (2012) conducted systematic wind pressure measurements to investigate the effect of wind pressures due to surrounding buildings on a low-rise building. Tecle et al. (2012) presented evaluations of wind-driven natural ventilation and studied the effects of the size and location of openings, room partitioning, opening cover screens, and internal volume correction, using a total of 156 pressure taps to examine both the external and internal pressure distributions over a low-rise building by wind tunnel experiments. Cheng et al. (2007) developed a wind tunnel experiment using both floating drag balance and pressure tapping in which form drag measurements were performed with a brass cube that fit 21 pressure tapings on the front and rear face; the authors confirmed more previously reported claims by integrating the pressure distribution on the roughness element. Furthermore, to better understand the effects of buildings in real urban areas or large scale models on airflow, it would be useful to find a method through which the drag force of real buildings or large scale models can be deduced by field measurements. If the function of the wind pressure and the drag force are known, then field measurements of the drag forces acting on buildings in real urban areas or large scale models can be realized by pressure measurements. However, in contrast to those performed to detect structure, studies concerning the effects of buildings on the atmosphere are very scarce. Therefore, by studying the effects of aerodynamic characteristics induced by non-uniform buildings through performing wind pressure measurements on building surfaces, direct drag measurements (determined by a floating drag