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Wind tunnel study on the morphological parameterization of building non-uniformity

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ABSTRACT

Because there is a lack of systematic studies on non-uniform buildings and most of them are qualitative research, this study implemented a morphological parameterization scheme to determine building morphology, which includes the frontal area index (λ_f), planar area index (λ_p), shape index (S_{BC}), and integrated non-linear coefficient (R). This scheme can systematically describe the non-uniformity of buildings with high precision. In addition, wind tunnel experiments were carried out to study the effects of the morphologic parameters of buildings on the drag force. A floating experimental platform was designed to measure the drag force of the whole area. The results showed that different levels of terrain roughness have little effect on the drag coefficient. In contrast, the frontal area index is the main factor that affects the drag coefficient when the wind direction changes. The drag coefficient was found to increase with increases in the frontal area index, density index, and shape index as well as decreases in the integrated non-linear coefficient.

1. Introduction

Turbulent airflow over urban areas can significantly affect urban climate. Similarly, urban surfaces have significant influences on airflow; thus, the relation between urban surface geometry and airflow is extremely complex. Understanding this relationship is important because it affects the dispersion of air pollutants, the thermal comfort of pedestrians and heat transfer between urban surfaces and the atmosphere. Because of the complex geometries and high roughness of urban underlying surfaces, which consist of various building shapes, as well as the drag of rough surfaces in a fully developed turbulent shear flow, attenuation of airflow occurs, and the performance of natural urban ventilation is greatly influenced. It should be noted that an important characteristics of urban buildings is non-uniformity, which causes the atmospheric energy and mass exchange to be extremely uneven and results in unique urban climates (Arnfield, 2003; Pielke et al., 2002). Additionally, the accurate estimation of wind characteristics within and above an actual urban canopy layer (UCL) is very difficult. Roth (2000) concluded that turbulence intensity, drag coefficient, turbulence length scale and some other characteristics obviously distinguish the non-uniformity of an urban underlying surface from an uniform underlying surface. He also indicated that the drag force due to buildings is one of the most important effects of urban surfaces on airflow. Hamlyn et al. (2007) used regular block arrays to measure pollutant exchange and developed a simple network approach. They concluded that the limitation of the simple approach is the inadequacy of the well-mixed assumption among tall buildings. Regarding urban pollutant dispersion, Blocken et al. (2008) compared results from three numerical simulations with results from three experiments and indicated that there are still many sources of error in numerical simulations of pollutant dispersion in the built environment.

In recent decades, methodologies concerning the aerodynamic features of various building geometries have mainly included experiments and numerical simulations, where the experimental method is divided into field measurements and modeling experiments. Wind tunnel experiments are widely used in current research on the atmospheric boundary layer because of their precision, which is helpful in recognizing the essence of airflow. Many drag problems in the atmospheric boundary layer have been reported to be quite unlike Nikuradse's sand-roughness. Measurements with regular arrays of cubes were first reported by O′loughlin and Macdonald (1964) and O′loughlin (1965), who used both 'diagonal' and 'parallel' configurations. Then, Lettau (1969) proposed a relationship between the aerodynamic parameter roughness length (z_0) and the geometry of the rough ground cover. This formula has often been quoted in relation to urban roughness estimates and has been implemented for whole cities using detailed morphologic features, for example,

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Ogaki City, Japan (Takahashi et al., 1981). However, Lettau's method has been widely recognized to be not applicable when the roughness area density or the frontal area index increases beyond 0.2–0.3 (see the discussion in Macdonald et al., 1998). Because this formula estimates z_0 from regular array geometries, it cannot accommodate high roughness densities and various obstacle shapes or layouts. Additionally, Wooding et al. (1973) reviewed many early research studies that focused on estimating the drag of various roughness boundaries. They compared studies on regular arrays of roughness elements of various shapes in a turbulent boundary at high Reynolds numbers. They also presented an empirical drag formula based on their measurement results, which can be used in studies on soil erosion and plant growth in partially vegetated areas. After about three decades, Macdonald et al. (1998) derived an improved methodology that included an obstacle drag coefficient and displacement height. Then, Macdonald (2000) presented a simple urban-type surface model, which was modified from vegetative canopy flow, and derived mean wind profiles in an obstacle canopy. Cheng and Castro (2002) reported results from comprehensive wind tunnel experiments using many different urban-type surfaces with the same area density of 25%. In the experiments, they used 120° x-wire anemometry to measure the spatially averaged velocity, used laser Doppler anemometry to confirm the accuracy of the x-wire, and deduced the surface stress using measuring instruments on the roughness elements. They also compared a homogeneous surface and a random height urban-like surface. Hanna et al. (Hanna et al., 2002) compared the numerical simulation results obtained from a three-dimensional Large Eddy Simulation (LES) with experiments on a hydraulic water flume, which investigated four test cases consisting of two layouts (square and staggered) with two obstacle heights (1.5 and 0.5). Using direct numerical simulation (DNS), which agrees very well with data from wind tunnel experiments, Coceal et al. (2006) reported on the turbulent flow over urban-like regular arrays of cubical obstacles. Based on formal spatial averaging procedures, they investigated the canopy flow within and the rough wall boundary layer above the arrays. Rather than experiments, Kanda et al. (2004) used LES to calculate the turbulent flow within a city cube array explicitly, and they investigated the effects of cube area density (0–40%) on turbulent flow characteristics. With the same LES model, Kanda (2005) also investigated the turbulent organized structures (TOS) over different building arrays, such as square or staggered arrays.

In more recent years, Cheng et al. (2007) carried out wind tunnel experiments to investigate the effects of two different area densities (6.25% and 25%) and two array geometries (aligned and staggered) of uniform urban-type surfaces on aerodynamic characteristics, of which the surface drag was directly measured. They discussed different determination approaches for the roughness length and compared the surface shear stress, which was determined from either a roughness element pressure measurement or a total surface drag measurement, with the shear stress, which was determined from the Reynolds shear stress profile. Hagishima et al. (2009) carried out wind tunnel studies using 63 arrays designed to investigate the effects of various layouts (lattice-type square, staggered and diamond-shaped), wind directions (0° and 45°) and block heights (1L and 1.5L) combined with five obstacle packing densities (λ_p=4.3%, 7.7%, 17.4%, 30.9% and 39.1%) on three aerodynamic parameters: drag coefficient, roughness length and displacement height. Di sabatino et al. (2010) investigated the vertical variation of morphological parameters to capture the essential features of the flow and derived the relevant fluid dynamic parameters for use in an urban flow model. Comparing different packing densities, compact versus sprawling neighborhoods and street orientation, they indicated that the morphological indices in terms of average building height (H), planar area index (λ_p), frontal area index (λ_f) and so forth, may be used instead of the detailed building geometry within urban canopy models because those indices together synthesize the geometric features of a city. Ahmad Zaki et al. (2011) carried out wind tunnel experiments to study aerodynamic parameters such as the drag coefficient, roughness length and displacement height for seven kinds of random geometries in urban-like arrays with various packing densities (λ_p=7.7%, 17.4%, 30.9%, 39.1%, and 48.1%). Then, using a wind tunnel experiment, Ahmad Zaki et al. (2012) measured the pressure drag, total drag and wind profile to study urban wind-induced ventilation. They used rectangular block arrays with different roughness conditions (fetch length from 30H to 120H) and packing densities (λ_p=7.7%, 17.4%, and 30.9%) in staggered, square, and diamond layouts. In the experiments, they measured the spatial distribution of the pressure drag acting on the walls of elements and found that for staggered arrays, the pressure drag accounted for more than 95% of the total surface drag.

Based on this overview of previous research, it can be found that observations on turbulent flow structures above urban-like roughness are not in acceptable agreement, and research studies on the effects of building non-uniformity on turbulent airflow are insufficient. Most of those researches concern only the obstacle packing densities and layouts, and few of them investigate the frontal areas or shapes of obstacles. Additionally, the most commonly used block layouts are extremely simple, such as square and staggered, which are not usually found in real urban areas. Furthermore, because of the extreme complexity of urban non-uniform buildings, most of the numerical model research is not concerned with construction heterogeneity effects. Studies have generally estimated urban effects by simple modification of the relevant physical parameters. As an example, the existing canopy layer models (such as Kusaka et al., 2001 and Masson, 2000) cannot explicitly distinguish between buildings of different sizes or determine the building distribution, and most of these models need to be carried out with certain homogenization processes. Therefore, the real building distribution is intentionally changed into regular arrays with a certain aspect of feature repetition, and thus, the most important morphological characteristics of the buildings are lost. Fernando (2010) reviewed the fluid dynamics of airflow over urban areas in complex terrain and indicated that the main factor affecting local airflow patterns is topographic and anthropogenic activities and that basic fluid dynamics play a central role in explaining the observations of urban flow and in developing sub-grid parameterizations for predictive models.

Consequently, in this paper, wind tunnel experiments were designed and carried out to evaluate the effects of building non-uniformity based on four building morphological parameters: frontal area, packing density, shape and layout. In Section 2, we present the morphological parameterization of building non-uniformity. Based on those four parameters, Section 3 describes the details of the configuration of models and the experimental set-up. Subsequently, in Section 4, the results of the experiment are discussed, focusing on the effects of morphological parameters on aerodynamic characteristics, and the effect of terrain roughness is presented. This study is expected to help elucidate the effects of building non-uniformity on aerodynamic characteristics and to provide theoretical support for predicting both the urban wind environment and urban pollutant dispersion. In addition, this study may allow more accurate assessments of the urban thermal environment and improve the numerical precision of the urban canopy model.

2. Morphological parameterization of building non-uniformity

At present, research studies have not presented a unified theory of the effects of building non-uniformity on urban climates. The lack of such quantitative research directly restricts the development