Building and Environment 135 (2018) 94–103

Contents lists available at ScienceDirect

Building and Environment

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

A wind tunnel study of ventilation mechanism over hypothetical urban roughness: The role of intermittent motion scales

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ARTICLE INFO

Keywords:
Air exchange rate ACH
Drag coefficient C_d
Frequency spectra
Quadrant analyses
Street-level ventilation
Wind tunnel experiments

ABSTRACT

Urban morphology is a major factor governing the dynamics in atmospheric surface layers (ASLs) of which our understanding is rather limited. In this paper, wind tunnel experiments are conducted to characterize the flows over different types of urban roughness in attempt to demystify the mechanism of street-level ventilation in isothermal conditions. Hypothetical urban areas are assembled by idealized street canyons using aluminum square tubes (ribs) and plastic LEGO® bricks (cubes). The velocity components are sampled by hot-wire anemometry (HWA) with *X*-wire probes. The drag coefficient C_d ($= 2u_\tau^2/U_\infty^2$; where u_τ is the friction velocity and U_∞ the freestream wind speed) is used to measure the aerodynamic resistance ($3.588 \times 10^{-3} \leq C_d \leq 10.799 \times 10^{-3}$) and parameterize the street-level ventilation of urban areas. The results show that the air exchange rate ACH, as a measure of the aged air removal, is proportional to the root of drag coefficient (ACH $\propto C_d^{1/2}$), implying that rougher urban surfaces favor street-level ventilation. Quadrant analyses illustrate that ejection (Q2) and sweep (Q4) are enhanced by aerodynamic resistance so are the transport processes. Frequency spectra further demonstrate that the dynamics is dominated by large-scale motions ($f \times \delta/u_\tau \leq 10$; where f is the spatial frequency and δ the thickness of turbulent boundary layer) which are more energetic with increasing drag coefficient. The above findings collectively suggest the importance of ASL large scales to street-level ventilation. In addition to promoting ground-level mean wind speed, increasing urban roughness could be a solution to the air quality problems nowadays.

1. Introduction

Stagnant air degrades street-level ventilation in urban areas [1]. Massive construction modifies land feature and urban morphology that unavoidably weakens the aged air removal from urban canopy layers (UCLs) [2,3]. Vast majority eases the problems by promoting ground-level wind speeds which, however, is hard to implement in dense cities nowadays. Advanced understanding of the flows and transport processes in atmospheric surface layers (ASLs) is therefore necessary to enhance street-level ventilation in built environment, improving urban-area air quality [4,5].

In spite of its importance to urban stakeholders, our understanding of the mechanism for street-level ventilation is rather limited [6,7]. That is partly why our remedial measures were not as effective as expected so far. This study is therefore conceived, employing turbulent flows over rough surfaces as the theoretical platforms, to elucidate the dynamics over hypothetical urban areas. In particular, we focus on the intermittency and motion scales together with their effects on street-level ventilation. The findings could offer valuable information for architectural design and urban planning in compact, mega cities in the air quality perspective.

Effort has been sought to examine the flows over (hypothetical) urban areas for decades [8–10]. ASLs develop in response to the presence of building obstacles similar to the conventional rough-wall turbulent boundary layers (TBLs) [5,11]. Street canyons have been adopted in numerous urban-climate studies which were usually assembled by rib-type roughness elements such as bars or tubes in crossflows [12–15]. Wind tunnel results over a range of obstacles demonstrated that the height of roughness sublayer (RSL) and inertial sublayer (ISL) was closely affected by the surface roughness [10]. Flows transition from a smoother surface to a rougher one over rib-type roughness elements revealed that the RSL was growing after an abrupt change in aerodynamic resistance before developed into the ISL [16]. The study on the influence of additional small-scale roughness elements on the top of an array of larger two-dimensional (2D) obstacles with different roughness-element-height-to-separation (aspect) ratios (ARs = 1, 2 and 0.5) showed that both the turbulence intensities and the momentum transport were enhanced by the small-scale roughness

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https://doi.org/10.1016/j.buildenv.2018.02.031
Received 2 October 2017; Received in revised form 21 February 2018; Accepted 22 February 2018
Available online 28 February 2018

elements when the ribs were close to each other (ARs = 1 and 2) but not far apart (AR = 0.5) [15]. Hence, AR is not the only factor affecting the transport processes over street canyons that calls for another indicator for geometric configuration.

Apart from rib-type roughness elements, three-dimensional (3D) cube-type roughness elements were employed in wind tunnel experiments to examine urban flows [17]. Vertical profiles of mean wind speed and turbulence were studied over arrays of staggered and aligned cubes with uniform or random height [18]. The RSL was thicker over cubes with random height, arguing that ISL might not exist over extremely rough surfaces. The flows over arrays of cubic roughness elements were characterized by particle image velocimetry (PIV) and/or laser Doppler anemometry (LDA), from which two-point correlation, quadrant analysis and integral length scales were derived [19,20]. The effect of surface roughness on the aerodynamic parameters by altering the arrangement of cubic obstacles was studied [21]. It was shown that the drag was peaked at certain obstacle density [22,23]. Although various studies have evaluated the dynamics over different surface types in wind tunnel experiments, our understanding of quantitative ventilation assessments and their mechanism over urban roughness was rather limited.

Real urban morphology is practically too complicated, e.g. frontal area index λ_F ($= A_F/A_T$; where A_F is the frontal area and A_T the total area) and plan area index λ_P ($= A_P/A_T$; where A_P is the plan area; Fig. 1), are difficult to be measured for air quality analyses so indicators have been formulated to compare street-level ventilation performance quantitatively [24–26]. Mass transfer coefficients were commonly adopted to measure the transport processes across TBLs that were equally applicable to street-level ventilation performance [27,28]. Bentham and Britter [29] proposed the use of exchange velocity between the flows in and above the UCL to compare street-level ventilation that was subsequently applied to real inhomogeneous urban geometries as well [30]. Bady et al. [31] compared the reliability of several indicators originally designed for indoor ventilation efficiency, such as purging flow rate (PFR), visitation frequency (VF) and residence time (TP) for outdoor, street-level air quality assessment. The cavity wash-out time, which measures the time scale of mass exchange between street canyons and the ASL aloft, was demonstrated to quantify street-level ventilation performance [32]. Likewise, the concept of city breathability was proposed to analyze pollutant removal from urban areas [33]. Alternatively, from the intermittency point of view, flushing was used to assess the street-level ventilation performance in terms of instantaneous, large-scale turbulence structure prevailing across a street canyon [34]. Urban atmospheric mixing layer height (MLH) was also proposed to calculate the ventilation of an entire city [35]. Apart from VF, Hu and Yoshie [36] simply used the averaged wind speed ratio and the spatially-averaged normalized concentration to assess the street-level ventilation efficiency of a built area. A new design parameter, passage ratio, was then proposed to refine street-level ventilation in urban planning practice. More analogous indoor indicators, such as air change rates per hour and canopy PFR, were proposed to quantify outdoor ventilation capacity [37]. Recently, Lo and Ngan [38] proposed the use of tracer age and age spectrum to measure the ventilation efficiency of a street canyon. The authors also proposed the air exchange rate (ACH), which was subsequent partitioned into mean ACH and turbulent ACH, to diagnose the roof-level aged air (upward) removal from a street canyon [39]. ACH is used in this paper to assess the street-level ventilation performance mainly because of its close relation with the drag coefficient C_d ($= 2u_\tau^2/U_\infty^2$; where u_τ is the friction velocity and U_∞ the freestream wind speed) which is commonly used in wind engineering studies.

Most of the aforementioned indicators compare street-level ventilation in the expense of additional measurements or post-processing of the ventilation variables. Parameterizations, which estimate street-level ventilation utilizing readily available data, are cost-effective measures in particular during design stage. Among various flow variables, Chung and Liu [40] used large-eddy simulation (LES) to showcase the close relation between turbulent ACH and drag coefficient C_d that was subsequently verified by computational fluid dynamics (CFD) results using idealized street canyons of different geometry [41]. Afterward, CFD with the Reynolds-averaged Navier-Stokes (RANS) k-ε turbulence models was performed over various building morphology, such as street canyons of different ARs and buildings of different roof shape, to evaluate the analytical relation [42]. Moreover, in the mechanism perspective, it was revealed that the ventilation over hypothetical urban areas was largely governed by turbulent transport but not mean

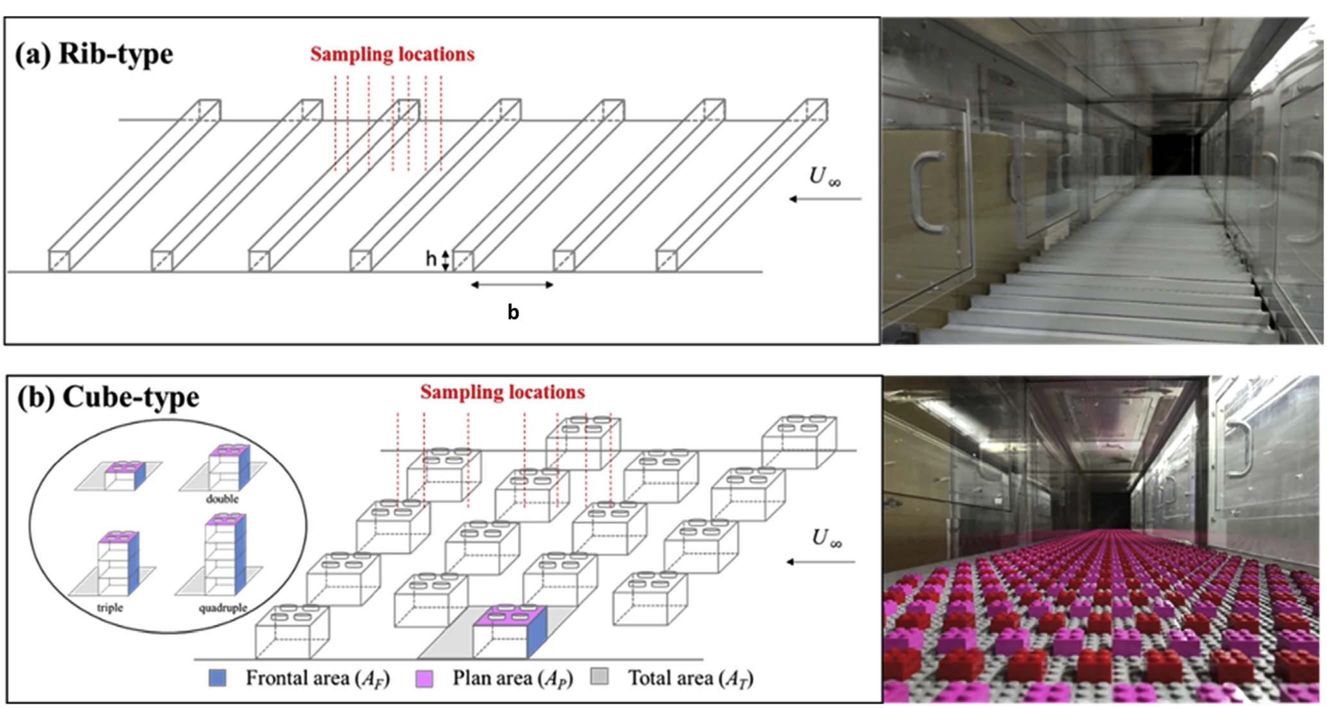

Fig. 1. (a) Rib- and (b) cube-type roughness elements in the wind tunnel experiments.