EXPERIMENTAL MODELLING OF FLOWS OVER VARIOUS IDEALIZED URBAN ROUGHNESS ELEMENTS

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Abstract:
Unlike open, flat rural areas, urban areas are comparatively more inhomogeneous because of the diversified shape/height of broad spectrum of buildings. Therefore, the mechanism of flows and pollutant dispersion, especially at the near-ground level, are complicated by this random geometry in which a detailed investigation is required in its parameterization. In this study, physical modelling in a wind tunnel is employed to study the ventilation and air pollution problems over urban areas. Rectangular aluminium bars are used to model the flat-roof buildings of 25-mm height. Reduced-scale models of different urban surfaces are formed by varying the building-height-to-street-width (aspect) ratio (ARs) among the buildings. Measurements over the aforementioned hypothetical urban surfaces of ARs 1, 1/2, 1/4, 1/8, 1/10, and 1/12 are performed in the wind tunnel in our department. The prevailing wind speed is kept at 2.5m sec^{-1} and the instrumentation is an in-house made 90^{o} X-hot wire anemometry. All the data collections are handled by the National Instruments (NI) data acquisition modules, NI 9239 and CompactDAQ-9188 hardware. The velocity calculation is carried out in the post-processing stage on a digital computer. Preliminary results show that the near-ground turbulence behaviour (within 2 to 5 times of the building height h measuring from the roof level) is sensitive to the changes in AR. The wider the streets (decrease in AR), the higher is the turbulence level. The street-level ventilation performance, which is measured by the air exchange rate (ACH), is found to be improved (increased ACH) with decreasing AR. A broad peak of ACH is observed in-between ARs 1/8, 1/10, and 1/12, suggesting the importance of fresh air entrainment to urban ventilation. The total ACH is further decomposed into its mean and turbulent components. Consistent with our previous large-eddy simulation (LES) results, it is found that urban ventilation is dominated by the turbulent component, i.e. air masses are driven by atmospheric turbulence (at least 80% of the total ACH). Additional measurements are currently undertaken on a variety of ARs and uneven building height to elucidate the complicated ventilation and pollutant removal mechanism over urban areas.

Key words: *Air pollution, Atmospheric turbulence, Street canyons, Wind tunnel modelling*

INTRODUCTION

With rapid urbanization and industrialization, public concern on urban environmental issues, such as air pollution problems due to heavy vehicular emission, have been increasing over the past decades. Unlike open, flat rural areas, urban surfaces are relatively inhomogeneous owing to the existence of buildings and obstacles with various heights and shapes. The aerodynamic interaction of such random rough surfaces complicates the near-ground flow and pollutants dispersion. The characteristic flows over most cities could be basically classified into skimming flow, wake interference and isolated roughness regimes (Oke, 1988) in which recirculating flows are observed within street canyons and their interaction with the outer flow aloft is limited. The street-level ventilation is subsequently weakened.

Given the complicated flows over irregular urban surfaces in multi-scale, it is impractical to resolve the detailed flows around/inside individual buildings. Studies on flows over various urban-like surfaces have been carried out using different methods, namely physical modelling (Macdonald et al., 2002) and numerical modelling (Cheng and Liu, 2012). For the flows in the near-ground region, on which the building groups impose direct effects, are characterised by the surface layer called inertial sublayer and roughness sublayer (RSL, Raupach et al., 1980). In particular in the RSL, where the length scale is around 2 to 5 times of the height of roughness elements, the flows are flanked by building obstacles such that a zone of reduced mean velocity but increased turbulence levels is developed. Although most urban inhabitants stay in this zone of complicated transport processes, only limited studies are available for the flows and turbulence in the RSL (Cheng et al., 2002).

In attempt to resolve the RSL flows over urban surfaces, a physical modelling approach is employed in this study to reveal the turbulence and pollutant transport in the near-ground region over urban surfaces. Experiments, which facilitate parametric tests in controllable environment, are conducted in a laboratory-scale wind tunnel to examine the flows over different types of hypothetical urban surfaces. While most of the previous studies either focused on the flows inside a street canyon or over an urban surface with limited configurations, this study is conducted to improve our understanding of the complex transport processes in the near-ground urban areas. The mean wind velocities and velocity fluctuations are measured in various configurations of idealized two-dimensional (2D) urban roughness surfaces of building-height-to-street-width (aspect) ratios (ARs) of 1, 1/2, 1/4, 1/8, 1/10 and 1/12. The full range of AR tested in the current study comprises the three key urban flow regimes (Oke, 1988).

MEHTODOLOGY

The experiments are carried out in the open-circuit wind tunnel in the Department of Mechanical Engineering, The University of Hong Kong (Figure 1). Measurements are collected in the test section of size 2000 mm (length) × 565 mm (width) × and 540 mm (height). Lego^{TM} elements were placed upstream the test section representing the (fully developed) background atmospheric boundary layer (ABL) over the street canyon models downstream. The mean velocity profile is fitted into the power law

$$\langle u(z)\rangle / \langle U_H \rangle = (z/H)^{\alpha} \qquad (1)$$

where U_H is the reference wind speed at the reference height H (it is the height of the turbulent boundary layer in this study). The profile exponent α is an empirical constant depending on roughness scales (and atmospheric stability in thermal stratification). For typical flows over urban-like surface in isothermal conditions, α is equal to 0.28. Fitting of the measured mean wind data by the power law Equation (1), the profile exponent for the current upstream roughness configuration is around 0.14 and a typical flow of the atmospheric boundary layer is simulated in the wind tunnel.

Figure 1. Experimental setup and idealized urban-like models.

Idealized roughness elements (Figure 1), comprising of up to 40 identical rows (depends on the ARs tested), are placed in the test section to simulate different hypothetical urban roughness. The roughness surfaces consist of 25-mm square aluminium bars that are aligned perpendicular to the prevailing flow and span the entire width of the wind tunnel. The experiments are performed in isothermal conditions and the prevailing wind speed is kept at U = 2.5m sec^{-1} throughout the experiments. The Reynolds number based on the prevailing wind speed and the height of the roughness elements

$$\mathrm{Re} = Uh/\nu \qquad (2)$$

is about 4150 that is large enough (> 3400) for flows independent from molecular viscosity (Hoydysh and Dabberdt, 1974).

The main instrumentation was an in-house made 90^{o} X-hot wire anemometry (HWA). The measurements are recorded on the midplane of the spannwise domain along the prevailing wind direction at different segments of the street canyon, starting from the roof level to the ceiling of the wind tunnel (Figure 2). In each configuration, a sample street canyon is selected near the end of the streamwise domain. Its roof level, i.e. the transverse between the mid-points of the upstream and downstream buildings, is divided into eight equal segments. The sampling time at each point is 45 sec that capture up to 80,000 valid velocity data. In the near-ground region (around 2h to 5h), up to 20 sampling points are recorded in order to measure the near-ground flows in details. LabVIEW software is employed to convert the analogue Wheatstone bridge output from the HWA to digital signal. All the data acquisition processes are handled by the National Instruments (NI) data acquisition modules, NI 9239 and CompactDAQ-9188 hardware. Velocity conversion was carried out in the post-processing stage on a digital computer.

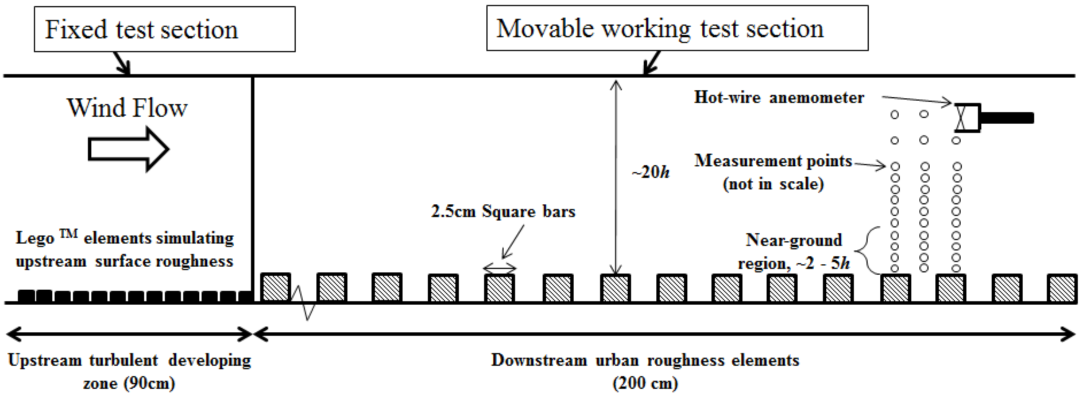


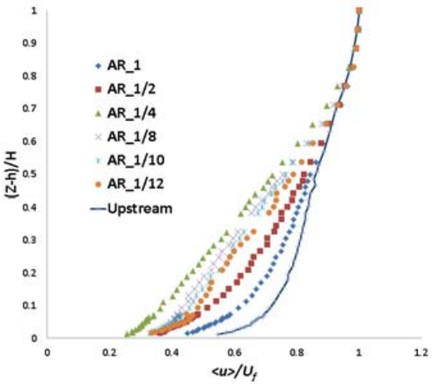
Figure 2. Schematic of the instrumentation details.

RESULTS AND DISCUSSIONS

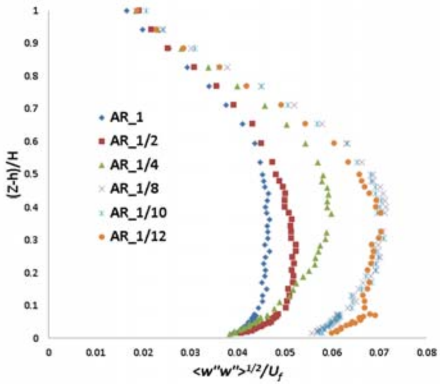
The profiles of mean streamwise velocity and vertical velocity fluctuations measured at the sample street canyon of different ARs near the end of the streamwise domain are shown in Figure 3. Each of these profiles is the ensemble averaged result of the eight profiles over the sample street canyon in the streamwise direction.

For the mean velocity, the profile in the developing section upstream the urban roughness elements is also shown in the plot. The measured values are normalized by the characteristic velocity scale U_f which is the free-stream velocity along the segment. The characteristic length scale is the boundary layer thickness H that is 260 mm (approximately 10 times of the height of roughness elements) for all the street canyon models tested. When the flows are entering the test section, the original upstream velocity profile is modified by the change in surface roughness (toward a rougher surface). In the cases of wider streets (smaller ARs), the mean flow speeds are dropped compared with their narrower counterparts. The reduced flows are mainly due to the larger aerodynamic resistance exerted from the street canyons of smaller ARs (rougher surfaces).

Profiles of vertical velocity fluctuations $\langle w''w''\rangle^{1/2}$ is also depicted in Figure 3. Similar to the mean velocity profiles, the ensemble average of the eight vertical segments is plotted whose value is normalized by U_f. In the RSL at the near-ground level ($2h < z < 5h$), $\langle w''w''\rangle^{1/2}/U_f$ increases with decreasing AR (widening in street width). Comparing the two extreme cases, ARs equal 1 and 1/12, the difference in the near-ground turbulence level is up to 50% that agrees with the observation available in literature (Oke, 1988). In the skimming flow regime (AR = 1), the interaction between the street-level recirculation and the outer prevailing flows aloft is limited because of the closely packed building elements, resulting in the reduced turbulence levels. When the AR is decreasing, the flows change to the wake interference and isolated flow regimes. A secondary flow is then initiated by the downward entrainment, reinforcing the recirculation. As a result, the interaction between street-level recirculation and outer flows is enhanced that in turn promotes the turbulence levels.

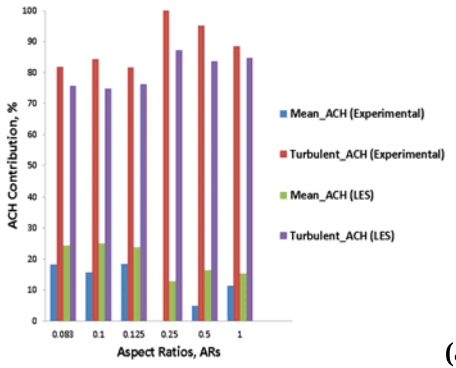


(a)

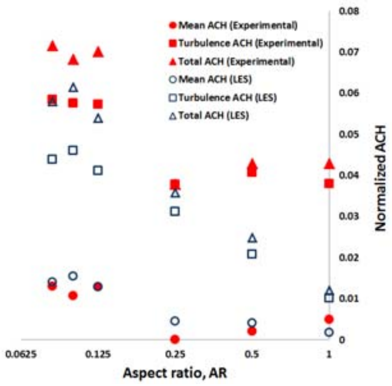


(b)

Figure 3. Vertical profiles of normalized (a) mean streamwise velocity and (b) vertical velocity fluctuation at various aspect ratios tested.



(a)



(b)

Figure 4. (a) Decomposed air exchange rate (ACH) and (b) dimensionless ACH plotted against ARs.

Air exchange rate (ACH) measures the rate of air removal from a street canyon that estimates the ventilation performance of idealized urban areas (Liu et al. 2004). Its mathematical definition is

$$ACH = \frac{1}{\lambda}\int_{0}^{\lambda}\int_{\Gamma_{roof}} w_{+}\,dxdt \tag{3}$$

where the subscript + signifies that only the upward flows are considered and the subscript roof signifies the roof-level properties of the street canyon. To look into the ventilation mechanism, ACH is further decomposed into its mean and turbulent components

$$ACH = \overline{ACH} + ACH''. \tag{4}$$

Velocity data across a period (the transverse between the mid-points of the upstream and downstream buildings) of the sample street canyon are collected and the corresponding ACH is calculated by the mean velocity and the velocity fluctuation in the vertical direction.

Figure 4a compares the decomposed ACHs as functions of ARs. ACH” consistently dominates the total ACH (at least 80% of the total ACH) for all the models tested. Although the contribution from mean ACH is slightly increased at smaller ARs (the street is wide enough that the mean flow can reach down to the ground level), it is suggested that the ventilation over urban surface is mostly governed by atmospheric turbulence. Figure 4b illustrates the general ACH behavior over different ARs. ACH increases with decreasing AR and a broad peak is observed at ARs 1/8, 1/10 and 1/12. The over-predicted ACH at AR 1 and 1/2 as observed in the current results could be instrumentation errors. In the cases of large ARs (narrow streets), the size of HWA sensor is comparable to that of street canyons. As such, part of the upward flows could be blocked and local turbulence is over-generated, leading to the over-predicted ACH. Nonetheless, the current experimental results compare well with our previous LES data (Wong and Liu, 2012).

CONCLUSION

A wind tunnel study is performed to examine the flows and ventilation performance over urban-like surfaces using idealized building elements. Idealized street canyon models of ARs 1, 1/2, 1/4, 1/8, 1/10 and 1/12 are tested. The flow field in the wind tunnel is measured by an in-house made 90^o hot-wire anemometry. The near-ground (within 2 to 5 times of the building height *h* measuring from the building roof level) turbulence is relatively sensitive to the changes in street canyon configuration. The vertical velocity fluctuation $<w''w''>^{1/2}/U_f$ increases with decreasing ARs (widening in street). Besides, the ACH over different tested models is calculated to compare the ventilation performance over urban areas. It is found that the ventilation over idealized urban areas is dominated by turbulent transport (over 80%), suggesting that atmospheric turbulence is essential to city ventilation. Additional measurements are required on a variety of urban-like surfaces with a broad range of ARs, building height variability, and friction velocity in order to seek for a thorough understanding of the complex transport processes and pollutant dispersion mechanism over urban areas.

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