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Citation	The 2013 European and African Conference on Wind Engineering (EACWE 2013), Cambridge, UK., 7-11 July 2013.
Issued Date	2013
URL	http://hdl.handle.net/10722/190039
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Experimental study on near-ground boundary layer response to the change in different patterns of urban-type surface

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Abstract

The flow behaviour over various two-dimensional (2D) urban-type surfaces was investigated in a laboratory wind tunnel. Square aluminium bars of size 2.5 cm were used to represent flat-roof buildings and the building separation was adjusted to fabricate various types of urban surface of building-height-to-street-width (aspect) ratios of 1, 1/2, 1/8, 1/10 and 1/12. Mean velocities and velocity fluctuations were measured with a 90^{o} *X*–hotwire anemometry. The current results compare well with our previous large-eddy simulation (LES). Analysis of the turbulence characteristics for different urban surfaces was performed in attempt to examine the near-ground boundary layer response to various street-canyon configurations.

1 Introduction

With rapid development in modern cities, the associated drawbacks on environment and urban climate have been affecting the human society since the last decade and are continuously intensified. Dense transport network results in building up high pollutant levels, while these elevated pollutant levels are closely related to the urban morphology. In contrast to rural terrain, urban configuration is relatively inhomogeneous due to the existence of large groups of buildings of various heights and shapes (a form of random roughness), resulting in the limited interaction between the cavity flows and the outer urban boundary layer (UBL) which in turn complicates the urban-area flows and pollutants dispersion. Heavy traffic emission and isolated flow condition in urban areas combine together resulting in the elevated pollutant levels and poor air quality. To maintain a sustainable living environment with clean air, it is vital to improve our understanding of these essential physical processes.

Street canyons are the basic building units comprising the urban canopy layer. An idealized two-dimensional (2D) street canyon unit, because of its simplicity, usually serves as the platform to study the fundamental mechanisms of ventilation and pollutant removal in urban areas. Oke (1988) classified the flows in a 2D street canyon into three characteristic regimes, namely, isolated roughness, wake interference and skimming flow, according to the building-height-to-street-width (aspect) ratio *h/b*. The skimming flow regime, signifying the characteristic street-level airflow surrounded by high-rise buildings, is our major concern nowadays. In this case, the recirculating flow inside the narrow street canyon is isolated from the UBL leading to poor ventilation. Indeed the flows over urban areas, is basically turbulent flows above roughness. In the boundary layer over rough surfaces, it is mainly characterised by the surface layer called inertial sub-layer and the roughness sub-layer (RSL, Raupach et al., 1980). In the RSL, whose length scale is estimated to be around 2 to 5 times of the roughness height, the flow is strongly affected by the rough surface beneath in which a region of reduced mean velocities but enhanced turbulence levels is developed. However, there are only limited studies on the boundary layer flows over near-ground urban areas, especially the turbulence behaviour, because of the complicated transport features (Cheng et al., 2002).

In the current study, a physical modelling approach is employed to initiate a long-term wind tunnel project that attempts to study the air pollution problems over urban areas. Although computational fluid dynamics (CFD) is one of the favourable approaches to the problem, laboratory-scale studies serve the purpose of validating numerical models and offer an effective way to simulate the flows over different surfaces in controllable environment as well. Together with CFD findings, complement solutions with experimental and numerical study are necessary to elucidate our understanding of the physics of urban air pollution. In our previous work, focus had only been put developing different numerical models (Liu et al. 2005, Cheng and Liu, 2011, Liu et al. 2011) while had unavoidably overlooked the results of laboratory measurements. This project is thus conceived to address the problems using another approach that attempts to arrive a complementary solution. Many of the literatures (Louka et al. 2002; Kovar-Panskus et al. 2002; Chang and Meroney 2003 and Caton et al. 2003) had used both laboratory measurements and numerical models concurrently. Analogously, the results obtained from this study are compared with our previous numerical models.

Ahmad et al. (2005) carried out a detailed review on the wind tunnel studies on urban street canyon flows and air pollution problems. However, most of the previous studies only focused on the flows inside a street canyon with rather limited configurations (Johnson and Hunter 1998, Kovar-Panskus et al. 2002) and unavoidably overlooked the role of turbulence in city ventilation. In order to enrich our understanding of the complicated transport processes in near-ground urban areas, flow behaviours over 2D urban roughness surfaces is examined in this paper. Measurements of mean wind velocities and velocity fluctuations over hypothetical urban surfaces consisting of 2D roughness elements with various configurations of building-height-to-street-width (aspect) ratios (ARs) of 1, 1/2, 1/4, 1/8, 1/10 and 1/12 were performed. The full range of ARs tested in the current study comprises the three key urban flow regimes (Oke, 1988). The objective of this study is to investigate how the change in urban morphology modifies the flow and turbulence behaviours in a turbulent boundary layer over urban-like roughness. Besides, the current measurement results are compared with our previous LES work to formulate a complementary solution (Wong and Liu, 2013).

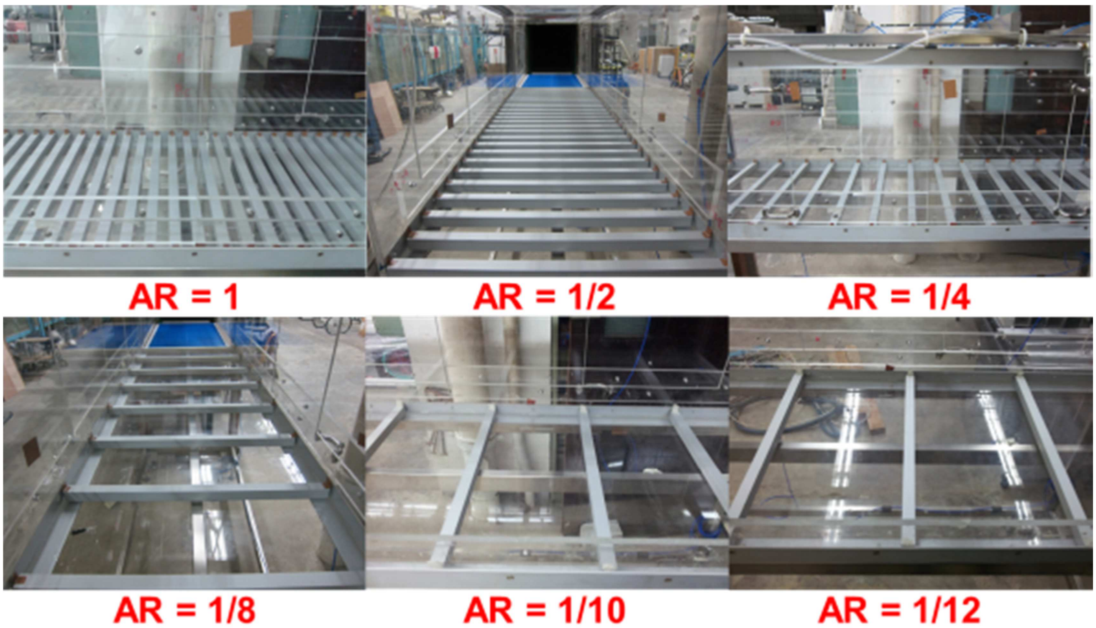

Figure 1: Different models of urban-type rough surface tested.

2 Experimental Set-up

The experiments were performed in an open-looped wind tunnel in the Department of Mechanical Engineering, The University of Hong Kong. Measurements were collected in a (movable) test section of 2,000 mm long, 565 mm wide and 540 mm high. Lego TM elements were placed upstream of the test section that represents the ambient surface roughness to generate a turbulent atmospheric boundary layer (ABL) to facilitate the development of the downstream ABL over the street canyon models. The mean velocity profile is fitted into the power law

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

where U_H is the reference wind speed at the reference height H (turbulent boundary layer thickness in this study). The profile exponent α is an empirical constant depending on the nature of the roughness amd the atmospheric stability in thermal stratification. It is equal to 0.14 and 0.25 for typical flows over natural terrain and urban surfaces, respectively, in isothermal conditions. Fitting the wind tunnel data to Equation (1) shows that, the profile exponent for the current upstream roughness configuration is around 0.14 to 0.15, simulating typical ABL flows in the wind tunnel.

A model of hypothetical urban surface was formed by reduced-scale roughness elements which are made of 25-mm square aluminium bars with their principal axes normal to the prevailing wind direction. The AR of the cavities between the bars was varied in attempt to simulate different types of urban morphology and to examine its effect on the flows developed above the roughness elements (response of UBL). Idealized roughness elements, comprising of up to 42 rows (depends on the AR of street canyons tested), were placed on the floor of the test section. Measurements were performed for six configurations of urban-type surfaces (ARs = 1, 1/2, 1/4, 1/8, 1/10 and 1/12; Figure 1), covering the full range of the three key urban flow regimes (Oke 1988). The first two arrangements correspond to skimming flow, AR = 1/4 falls into the (sensitive) wake interference flow, and the last three belong to isolated roughness flow regime. It is our intention to examine the general behaviours, both the mean flow and turbulence, over idealized urban surfaces. Therefore, systematic tests on a broad range of ARs comprising the three key urban flow regimes were performed. Finally, in order to evaluate the changes in UBL over different arrangements of street canyon models, the mean-flow profiles of the upstream roughness were also recorded for comparison purposes.

The experiments were performed in isothermal conditions. The prevailing wind speed was kept at U_f = 2.5 m sec^{-1} throughout the experiments. The Reynolds number based on the prevailing wind speed and the height of the test section (*D*) or buildings (*h*) is about 112,500 and 4,150 (in room temperature and pressure) that both are large enough for flows independent from molecular viscosity. Vertical profiles of velocities of each model were measured with an in-house made 90^o *X*–hot wire anemometry. The measurements were recorded on the mid-plane of the spannwise domain along the streamwie direction (Figure 2). 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. Vertical profile measurements starting at the roof level of the building elements up to the top boundary of the test section were performed on each segment in order to minimise the streamwise instrumentation errors. At each measurement point, the two-component (streamwise and vertical) mean and fluctuating velocities were collected for the duration of 45 sec (80,000 data). The core objective of this paper is to examine the near-ground boundary layer response to the changes in urban morphology. Therefore, particularly in the near-ground region (0 mm to 125 mm measuring from the building roof level), up to 20 sampling points were recorded with the help of a precise traversing system (a XYZ table with a LabVIEW motor control unit) in order to reveal the near-ground flows in details. LabView software was employed to convert the analogue bridge output from hot-wire into digital signal and all the data acquisition processes were handled by the NI data acquisition modules, NI 9239 and CompactDAQ-9188 hardware. Velocity mapping was carried out in the post-processing stage on a desktop PC.

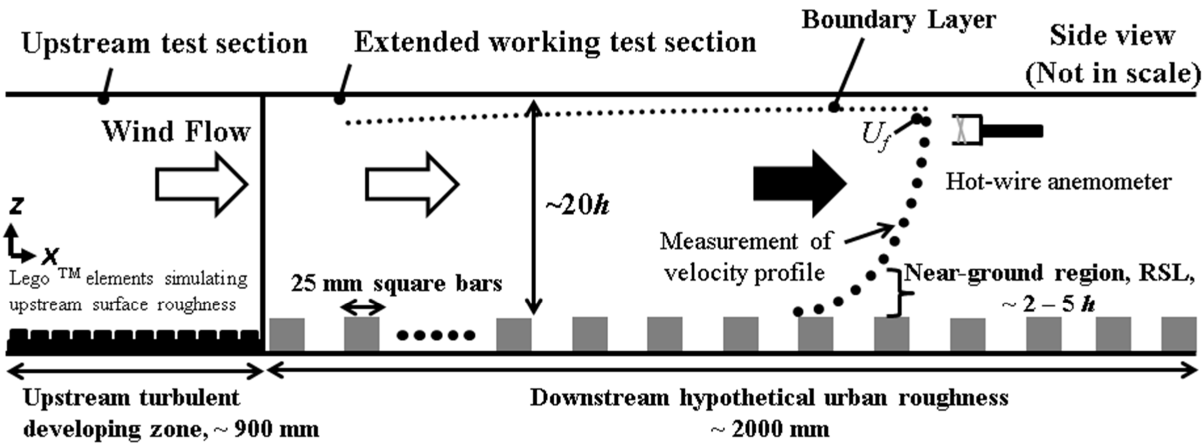

Figure 2: Schematic of the experimental setup

3 Results and Discussion

In this section, preliminary results of the mean and fluctuating velocities are reported. In particular to the model of unity AR, its experimental profile measurements are compared with our previous large-eddy simulation (LES, Wong and Liu, 2013) results with the aim to test the accuracy of both the numerical model and current experimental work, as well as to formulate a complementary solution approach. Afterward, the effect of different urban morphology on the near-ground boundary layer structures (both mean flows and turbulence properties) is discussed.

3.1 Comparison of experimental and LES results

Our previous LES study used a computational domain of height, $D = 8h$, where h is the height of the roughness elements. Free-slip boundary condition is applied to the upper boundary and periodic boundary condition is applied to the horizontal domain extent so that an infinitely repeating 2D street canyon is modelled. The prevailing flow is driven by a background pressure gradient. The information of the LES models and the numerical methodology is detailed elsewhere (Wong and Liu, 2013).

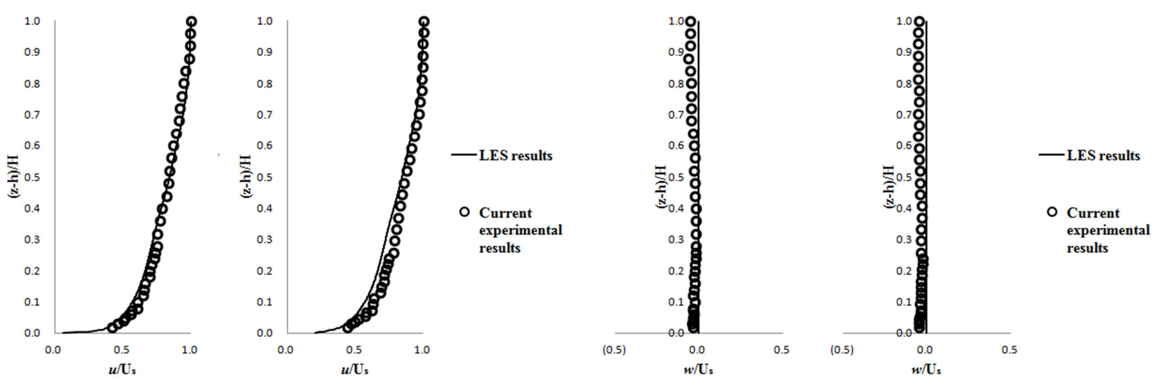

Figure 3: Profiles of the normalized streamwise <u> /U_f and vertical <w> /U_f velocities

As shown in Figure 3, both the streamwise and vertical mean wind velocities $\langle u \rangle$ and $\langle w \rangle$ are normalized by the free-stream velocity U_f which is measured at the top of the boundary layer (Figure 2), while the characteristic length scale is the boundary layer thickness H (= 260 mm; approximately 10 times of the height of roughness elements). The current experimental results are generally in good agreement with our LES results. Whereas, a minor over-predicted value in the streamwise velocity is observed in the current measurements that could be caused by the difference in domain size between the LES and the wind tunnel. The current wind tunnel domain height is approximately 20*h* (aluminium bars of height h = 25 mm are used) while the LES model is 8*h* only. In addition to the horizontal direction, though the measurements are taken on the mid-plane in the spanwise direction, the width of the building models are relatively finite compared with the periodic boundary condition in the spanwise direction in the LES model. Besides, the flow field in the LES model does not experience any end/side wall effects. Whereas, in the experiments, the side wall of the wind tunnel test section may exert additional shear on the flows. Therefore, secondary flows may evolve due to the interaction between the street-canyon vortices and the side walls of the wind tunnel. This limitation in the wind tunnel experiments could possibly cause a slightly larger value of streamwise velocity as observed.

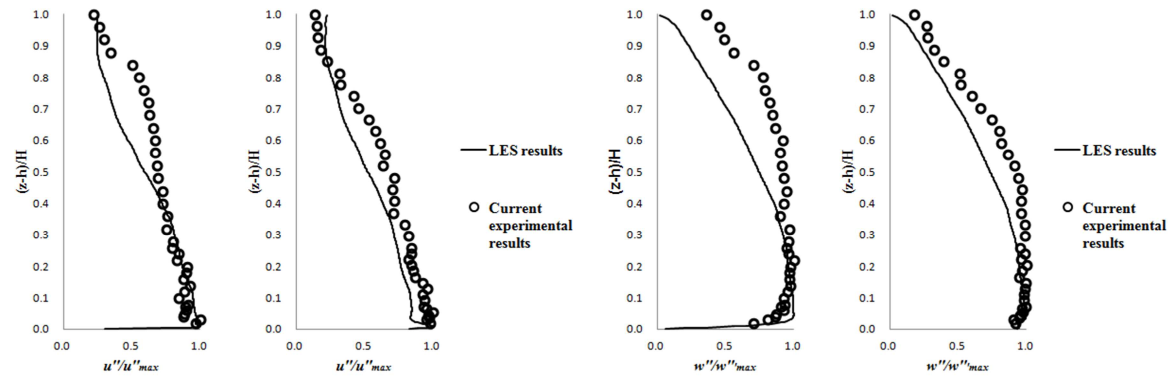

Figure 4: Normalized streamwise $\langle u''u'' \rangle^{1/2}/u''_{max}$ and vertical $\langle w''w'' \rangle^{1/2}/w''_{max}$ velocity fluctuations

On the other hand, Figure 4 compares the velocity fluctuations, $\langle u''u'' \rangle^{1/2}$ and $\langle w''w'' \rangle^{1/2}$, above the roughness elements. Alike the mean velocity profiles, the characteristic length scale is the boundary layer thickness *H*. It is noticeable that the results of LES and wind tunnel agree well with each other. A local maximum is observed slightly above the building roof level that decreases in the vertical direction. Moreover, both results consistently show the trend that $\langle w''w'' \rangle^{1/2}$ is peaked at a higher elevation compared with that of the peaked $\langle u''u'' \rangle^{1/2}$. This difference can be explained by the prevailing flow in the streamwise direction, hence, the energy transfer is in the order from the streamwise to spanwise and then to vertical directions finally.

This section serves as a preliminary comparison between the wind tunnel and numerical simulations. It should be emphasised that the wind tunnel setup is not tailor made to the numerical model, or the other way round. It is our intention to enrich our current understanding of the flow and pollutant dispersion mechanism over urban areas with two different approaches. Moreover, it is expected that both methods, arriving consistent results, could constitute a complementary solution. The reasonable agreement shown proves that the current methodology is in the right course of work and the results could serve as the preliminary data base for our development of future experimental modelling design on the dispersion study. Furthermore, our LES model is of a good accuracy on predicting the flow structure over 2D idealized roughness.

3.2 Mean flows and turbulence behaviours over various urban-like surfaces

In this section, the measurements of the current wind tunnel experiments are presented. The profiles of mean streamwise velocities and vertical velocity fluctuations measured at the sample street canyon of different ARs near the end of the streamwise domain are shown in Figures 5 and 6, respectively. Each of the profiles represents the ensemble averaged results of the eight segments over the sample street canyon in the streamwise direction.

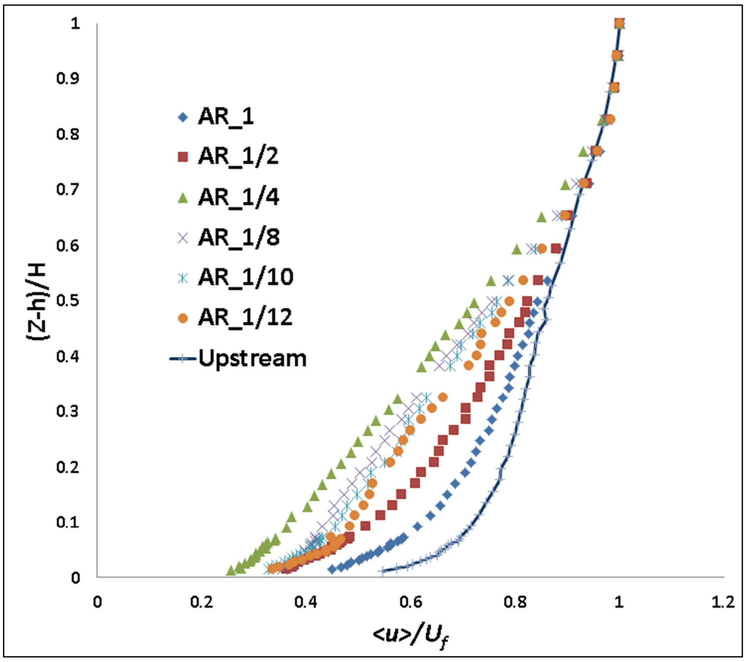

Figure 5: Comparison of the streamwise mean velocities at ARs of 1, 1/2, 1/4 1/8, 1/10 and 1/12.

For the mean velocity, the profiles in the developing section upstream the urban roughness elements are also depicted in the figure. 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 (= 260 mm; approximately 10 times of the height of roughness elements) for all the street canyon models tested. When the flows are entering the urban-like surfaces, the original upstream ABL structure is modified by the changes in surface roughness (towards a rougher surface). For all the cases tested, a zone of reducing flow speed is observed in-between the roof level and the mid-level of the turbulent boundary layer (0.5H which is approximately equal to 5h in the RSL). For the cases of wider streets (smaller ARs), the mean flow speeds are dropped comparatively greater than those of narrower streets. This finding could be explained by the higher aerodynamic resistance exerted from the street canyons of smaller ARs (rougher surfaces) on the flows.

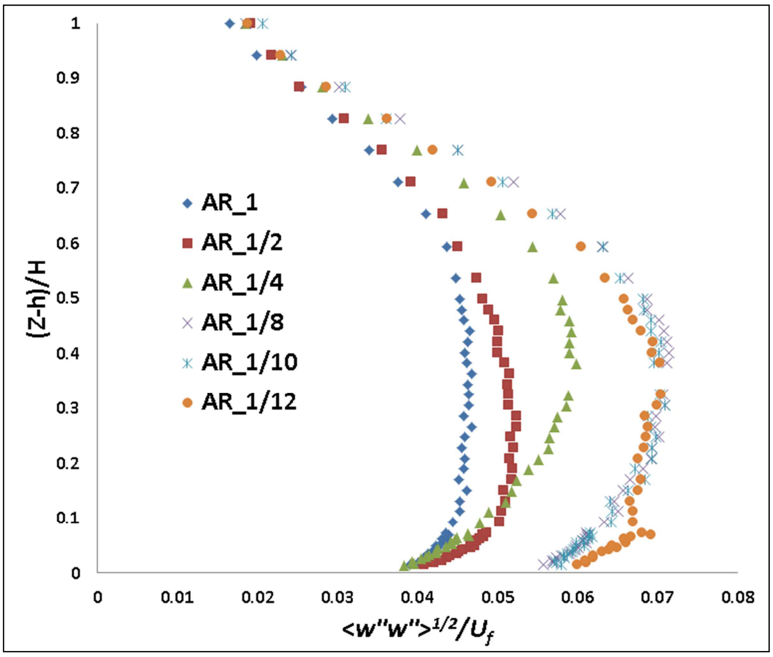

Figure 6: Comparison of the vertical velocity fluctuations at ARs of 1, 1/2, 1/4, 1/8, 1/10 and 1/12.

Profiles of vertical velocity fluctuations $<w''w''>^{1/2}$ are depicted in Figure 6. Similar to the mean velocity profiles, the ensemble average of the eight vertical segments is plotted whose values are normalized by U_f. Consistent with the mean wind profiles, the RSL is revealed at the near-ground level ($2h < z < 5h$). The dimensionless vertical velocity fluctuation $<w''w''>^{1/2}/U_f$ increases with decreasing ARs (widening in street width). Comparing the two extreme cases, ARs equal 1 and 1/12, the difference in the near-ground turbulence levels is up to 50% that agrees well with the classification available in literature (Oke, 1988). In the skimming flow regime (AR equals to 1 or 1/2), 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. The prevailing flows in the UBL core could reach down to the street level. A secondary flow is then initiated by the downward entrainment, reinforcing the street-;level recirculation. As a result, the interaction between street-level recirculation and outer flows is enhanced that in turn promotes the near-ground turbulence levels.

For both the mean and turbulent flow properties, the effects of the roughness elements are rather shallow that are mainly limited in the RSL region. On the other hand, the flow properties in the UBL core are fairly uniform. These results provide further evidence for the influence of urban morphology on the near-ground structure of the turbulent boundary layer.

4 Conclusions

Flows over various idealized urban-type surfaces of street canyons of ARs 1, 1/2, 1/4, 1/8, 1/10 and 1/12 were modelled in a laboratory-scale wind tunnel. The turbulent boundary layer over the idealized urban roughness elements is measured with in-house made 90^{o} *X*-hotwire anemometry. The mean flow and turbulence characteristics of unity AR street canyon arrangements were compared with our mathematical modelling results for validation purposes. The current experimental results agree reasonably well with our previous LES data. Besides, the effect of urban morphology on the boundary layer structure is also examined. The result suggests that the level of turbulence generated, particularly at the near-ground level, is of an increasing trend with widening street width (i.e. a decrease in AR). However, this increasing trend is stopped at the AR equal to 1/8 and a broad peak is observed across ARs 1/8, 1/10 and 1/12. Additional measurements are undertaken on a variety of urban surfaces with a broad range of ARs, building height variability, and friction velocity in order to elucidate the complicated transport processes and pollutant dispersion mechanism over urban areas.

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