October 2018

The spanwise structure of the roof-level turbulence in a street canyon flow

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A thesis submitted in partial fulfillment of the requirements for the degree in Master of Engineering Science

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Abstract

In the present work, for the first time, the spanwise organization of turbulent flow along an urban street canyon subjected to wind normal to the street axis using a boundary layer wind tunnel is systematically investigated. The effect of upstream roughness and canyon width on the turbulence in a street canyon flow is presented. Measurements in a horizontal plane were conducted at near roof-level of a street canyon using Stereoscopic Particle Image Velocimetry. Three upstream roughness arrays and two canyon width \((W)\) to height \((h)\) aspect ratios \((AR = W / h = 1\) and 3) were investigated. The results show a significant effect of upstream roughness on the mean turbulent statistics, two-point correlations and integral length-scales. A multi-scale quadrant analysis revealed that the average size of ejection and sweep events are affected by upstream roughness and canyon geometry, with the wake-interference flow regimes producing the largest. Finally, the analysis of the mean turbulent statistics, temporal correlations, instantaneous multi-scale turbulence and quadrant events yield a significant difference between the wake-interference flow regimes and the skimming flow regimes.

Keywords

Boundary layer, Street canyon, Turbulence, Particle Image Velocimetry, Wind tunnel.
Turbulence in a street canyon flow

*The present author, T M Jaroslawski is the owner of this image.*
Co-Authorship Statement

The present work is a collaborative effort by the present author, Dr. Eric Savory and Dr. Laurent Perret. The experimental work was supervised by Dr. Laurent Perret and was conducted at Ecole Centrale de Nantes in the Laboratoire de recherche en Hydrodynamique, Energetique et Environnement Atmospherique. The wind tunnel experiments were conducted by the present author. Dr. Perret and Mr. Piquet provided invaluable assistance in conducting and setting up the wind tunnel experiments. Both articles in the present work were completed with the present author as the primary author, however, Dr. Savory, Dr. Perret and Dr. Karin Blackman provided feedback during the writing process. Guidance in data processing was provided by Dr. Savory and Dr. Perret. Previous data obtained by Dr. Blackman was used to validate the present results.

A version of Chapter 2, the spanwise variation of roof-level turbulence in a street canyon flow, has been accepted for publication in Boundary Layer Meteorology (August 2018).

A version of Chapter 3, which investigates the spanwise variation of large-scale and small-scale sweep and ejection events in street canyon flow, will be submitted to Environmental Fluid Mechanics.

Chapter 4, summarizes the present work and provides recommendations for future work on street canyon and urban type flows.
Acknowledgments

I would like to thank Dr. Eric Savory for his instrumental help during the entire thesis process and Dr. Laurent Perret for his great assistance with the experiments, data processing and writing and for permitting the final stages of the thesis to be completed at ECN.

The present author would also like to thank the entire LHEEA research group for allowing to use the facilities at Ecole Centrale de Nantes, especially Mr. Thibaut Piquet for great technical support. I would like to thank Dr. Karin Blackman, for providing data and for her advice with writing.

I would also like to thank my colleagues in the AFM research group and the rest of my colleagues at The University of Western Ontario.

Darek i Beata, moje rodzice, dziękuję wam za trud i wsię rek włożony w moje wychowanie, za cierpliwość i dobre serce.

Nicolas my brother, and the rest of my close friends, your support has been fantastic.

I would like to thank Douglas Muzyka and his International Graduate Scholarship for providing funding during the summer stay in France. The Natural Sciences and Engineering Research Council (NSERC) of Canada for providing funding. The financial support of the French National Research Agency through the research grant URBANTURB N° ANR-14-CE22-0012-01 is also acknowledged.
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<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>$A_d$</td>
<td>total plan area ($m^2$)</td>
</tr>
<tr>
<td>$A_p$</td>
<td>plan area of obstacles ($m^2$)</td>
</tr>
<tr>
<td>$d$</td>
<td>displacement height (m)</td>
</tr>
<tr>
<td>$h$</td>
<td>height of the canyon (m)</td>
</tr>
<tr>
<td>$\bar{\tau}$</td>
<td>time averaged quantity (overbar)</td>
</tr>
<tr>
<td>$Je$</td>
<td>Jenson number ($h / z_0$)</td>
</tr>
<tr>
<td>$L$</td>
<td>length of the canyon (m)</td>
</tr>
<tr>
<td>$L_{ii,x}$</td>
<td>streamwise integral length scale (subscripts $ii$ represent fluctuating velocity)</td>
</tr>
<tr>
<td>$L_{ii,y}$</td>
<td>spanwise integral length scale (subscripts $ii$ represent fluctuating velocity)</td>
</tr>
<tr>
<td>$Re$</td>
<td>Reynolds number ($U_e h / \nu$)</td>
</tr>
<tr>
<td>$R_{ii,x}$</td>
<td>streamwise two-point correlation coefficient (subscripts $ii$ represent fluctuating velocity)</td>
</tr>
<tr>
<td>$R_{ii,y}$</td>
<td>spanwise two-point correlation coefficient (subscripts $ii$ represent fluctuating velocity)</td>
</tr>
<tr>
<td>$t$</td>
<td>time (s)</td>
</tr>
<tr>
<td>$T$</td>
<td>measurement time (s)</td>
</tr>
<tr>
<td>$T_x$</td>
<td>integral time-scale (s)</td>
</tr>
<tr>
<td>$u^*$</td>
<td>friction velocity ($m s^{-1}$)</td>
</tr>
</tbody>
</table>
\( U_e \)  
freestream velocity (ms\(^{-1}\))

\( \overline{U, V, W} \)  
mean streamwise, spanwise and vertical fluctuating velocities (ms\(^{-1}\))

\( \overline{V_f} \)  
mean quadrant filtered spanwise velocity (ref. \( x = 0, y = 0 \))

\( u', v', w' \)  
streamwise, spanwise and vertical fluctuating velocity components, respectively (ms\(^{-1}\))

\( U, V, W \)  
streamwise, spanwise and vertical instantaneous velocity components, respectively (ms\(^{-1}\))

\( \overline{\overline{u w}} \)  
Reynolds shear stress (m\(^2\)s\(^{-2}\))

\( x, y, z \)  
streamwise, spanwise and vertical directions, respectively.

\( z_0 \)  
aerodynamic roughness length (m)

\( Z^+ \)  
dimensionless wall coordinate

**Greek Symbols**

\( \tau \)  
time delay (s)

\( \delta \)  
boundary layer thickness (m)

\( \sigma_u, \sigma_v, \sigma_w \)  
streamwise, spanwise and vertical velocity standard deviations (ms\(^{-1}\))

\( \nu \)  
kinematic viscosity (m\(^2\)s\(^{-1}\))

\( \rho \)  
density (kgm\(^{-3}\))

\( \lambda_p \)  
packing density \((A_p / A_d)\)
### Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>2D</td>
<td>two-dimensional</td>
</tr>
<tr>
<td>3D</td>
<td>three-dimensional</td>
</tr>
<tr>
<td>ABL</td>
<td>atmospheric boundary layer</td>
</tr>
<tr>
<td>AR</td>
<td>aspect ratio ((W / h))</td>
</tr>
<tr>
<td>FFT</td>
<td>fast Fourier transform</td>
</tr>
<tr>
<td>IBL</td>
<td>internal boundary layer</td>
</tr>
<tr>
<td>LAR</td>
<td>lateral aspect ratio ((L / h))</td>
</tr>
<tr>
<td>PIV</td>
<td>Particle Image Velocimetry</td>
</tr>
<tr>
<td>Q (1-4)</td>
<td>quadrant events, Q1 (inward interaction) Q2 (ejection), Q3 (outward interaction) and Q4 (sweep)</td>
</tr>
<tr>
<td>r.m.s</td>
<td>root mean square</td>
</tr>
<tr>
<td>RSL</td>
<td>roughness sublayer</td>
</tr>
<tr>
<td>SPIV</td>
<td>stereoscopic particle image velocimetry</td>
</tr>
<tr>
<td>TKE</td>
<td>turbulent kinetic energy, (\text{TKE} = 1/2(\sigma_u^2 + \sigma_v^2 + \sigma_w^2))</td>
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Chapter 1

Introduction

In the following chapter contains a general literature review explaining street canyon flows. The experimental methodology used in this field is summarized, including the techniques used in the present work. Finally, the objectives and purpose of this thesis are explained.

Air quality in urban environments is a critical issue in contemporary times; the resulting socioeconomic implications are of great concern. Pollution in the earth's atmosphere leads to human death, disease and harm to our natural resources. The World Health organization reports that in 2012, approximately 7 million people died because of air pollution. This finding confirms that air pollution is now the world’s largest single environmental health risk (WHO, 2014). The design of smart cities, is highly influenced by the flow of the air around and within them. Building configurations, size and shape influence energy potential and cooling in solar panels and other renewable sources of energy (Mauree et al., 2017) To mitigate the negative implications of pollution and to design efficient smart cities we must first understand the physical processes that govern the dynamic transport of air and pollutants in an urban environment.

The attempts to model the fluid dynamic and pollutant transport processes occurring in an urban environment, whether experimental or numerical, generally take one of two paths
(Savory et al., 2013). In the first, a scaled urban region, such as a downtown area in a metropolitan city, is used. If modelled properly, the results from a study of this type, can provide us with information about the physical processes in that specific downtown area. The second method entails the use of a simplified model, a street canyon or an array of obstacles that can be used for a more general understanding of the physical phenomena occurring. The use of a simple street canyon model can be more advantageous as it is difficult to interpret the fluid dynamic phenomena in a scaled city region (Savory et al., 2013). The cause and effect of an event or process is difficult to interpret, if a knowledge gap exists in the simplified case. It is of great importance that the fundamental fluid dynamic processes in a simplified model such as a street canyon are well understood, so that numerical models can be validated and experimental techniques improved.

1.1 The street canyon problem

Although the street canyon may appear to be simple, the physics are quite complex, therefore care must be taken when defining the problem. From a fluid mechanics point of view, a street canyon in an urban environment can be defined as; a set of surface mounted rectangular prisms or obstacles, immersed in a thick turbulent boundary layer. The flow domain can be divided into three areas: the oncoming atmospheric boundary layer (ABL), the street canyon itself and the shear layer interacting with both the atmospheric boundary layer and the street canyon. A general schematic of a street canyon is presented in Fig. 1. Referring to Fig. 1, the urban canopy layer is the region in the boundary below the mean height of the roughness obstacles \( h \), in this region the flow is influenced greatly by the thermal properties of the buildings and the local-scale flows developing from the geometry of the buildings (Oke, 1988). Above is the roughness sub-layer (RSL) where the shear layer is located. The RSL can be defined as being the distance from the surface to \( 2h-5h \). The RSL is the region where the flow is influenced by individual roughness elements, which is reflected in the spatial inhomogeneity of the mean flow (Castro and Chang, 2002). Finally, in the inertial sub-layer the effects of viscosity can be
neglected and it can be assumed the flow will depend directly on the size of the boundary layer.

![Diagram of atmospheric boundary layer and street canyon](image)

**Figure 1:** Schematic of the general street canyon problem, with the corresponding velocity profile on the right.

### 1.2 The boundary layer

A boundary layer will form on any surface but, in an urban environment, the terrain is sufficiently rough that the boundary layer generated by the wind is highly complex. Rotating flow and coherent turbulent structures are found in turbulent boundary layers. A coherent structure is a region of flow where a variable (such as velocity) exhibits a significant temporal/spatial correlation with itself or another variable. The correlation must be significantly larger than the smallest local scales of the flow (Robinson, 1991). A boundary layer can be divided into three regions: the viscous sub-layer, buffer region, and the logarithmic region. All these regions contain coherent structures with differing characteristics. A velocity profile displaying the different regions of the boundary layer is presented in Fig. 2. Here, \( Z^+ \) represents the wall coordinate, the dimensionless distance away from the wall. \( Z^+ \) is made dimensionless by the friction velocity \( u_\ast \) and the kinematic viscosity, \( \nu \). \( U^+ \) is the dimensionless velocity \( U^+ = \frac{1}{\kappa} \ln(Z^+) + C^+ \), \( \kappa \) denotes the Von-Karman constant and \( C^+ \) is a constant) parallel to the wall as a function of the distance away from the wall. The streamwise and vertical velocity fluctuations are denoted as \( u' \) and \( w' \), respectively. In the present work, the roughness length is denoted
by $z_o$ and the displacement height is denoted by $d$. The instantaneous velocities in the $x$, $y$ and $z$ directions are the steamwise ($U$), spanwise ($V$) and vertical ($W$) components, respectively. Time averaging is generally denoted by an overbar, the time-averaged mean velocity, $\overline{U}$, is defined as $\overline{U} = U(t) - u'(t)$ based on the Reynolds decomposition, $U(t)$ denotes the instantaneous velocity and $u'(t)$ the velocity fluctuation from the mean.

\[ \text{Figure 2: Typical turbulent boundary layer profile} \]

The development of the boundary layer is heavily dependent on surface roughness which, in an atmospheric boundary layer, is referred to as relative topography or roughness (Cook, 1995). In wind tunnel experiments the roughness (buildings, trees and urban centres) can be simulated using arrays of prisms, with their purpose being to simulate a realistic boundary layer found in the atmosphere. Roughness alters the wall shear, thus impacting the growth of the boundary layer (Volino et al. 2009). In wind tunnel experiments, three configurations are commonly used: (1) two-dimensional bars, (2) three-dimensional staggered blocks and (3) three-dimensional aligned blocks. An example of an upstream roughness array in a wind tunnel is presented in Fig. 3. The difference between a boundary layer forming over two-dimensional and three-dimensional roughness elements is in the scales of motion induced by those elements. Volino et al. (2009) observed that the scales of turbulence produced by three-dimensional
roughness elements were of the order of their height. The motions generated by two-
dimensional elements were found to be much larger than three-dimensional elements, 
they suspected this to be due to the width of the two-dimensional elements. Three-
dimensional roughness elements are generally preferred to two-dimensional elements 
because the latter tend to generate two-dimensional large coherent structures in the 
boundary layer, whereas three-dimensional blocks generate more realistic three 
dimensional structures (Savory et al., 2013).

Figure 3: One of the three upstream roughness configurations used in the present 
experimental work at Ecole Centrale de Nantes (France). The configuration in this 
figure consists of a 3D staggered cube array which is denoted as Rcu, refer to section 
1.8 for more details on the configurations used.

A street canyon is a bluff body, where the oncoming flow separates at the leading edge of 
the canyon. When the flow separates from the body, a shear layer is generated whose 
wake is large and highly complex where discrete vortices are generated by the flow 
separation (Tamura et al., 2013). The shear layer is a region of flow where there is a 
significant velocity gradient. Turbulent coherent structures in the wake of the canyon and
their interaction with the structures found in the oncoming boundary layer affect the dynamics of pollutant transport and ventilation within the canyon (Blackman et al., 2015). Sweep (downward and forward motions) and ejection (upward and backward motions) events are present in boundary layers and street canyon flows. Due to the conservation of momentum, the fluid has the tendency to move from regions of high momentum to regions of lower momentum. In a street canyon fluid and momentum entering the canyon from the separated shear layer is considered a sweep. Fluid and momentum exiting the canyon and interacting with the separated shear layer is considered an ejection (Perret et al., 2016). Quadrant analysis can be used to quantify these events, where an ejection event would correspond to the second quadrant (Q2) and a sweep event would correspond to the fourth quadrant (Q4). Quadrant analysis is a tool often used to quantify events occurring in a flow. It is the relation between $u'$ and $w'$, velocity components in the four quadrants located in a vertical plane aligned with the stream-wise direction and normal to the wall. This allows a description of the bursting process; a sweeping event would occur in quadrant 4 (Q4) and an ejection event in quadrant 2 (Q2), as illustrated by the large arrows in Fig. 4. Quadrant analysis allows for the direction of the Reynolds stress ($\overline{uu'}$), in the flow to be quantified (Robinson, 1991). The Reynolds stress is the correlation of the fluctuating streamwise ($u'$) and vertical ($w'$) velocities. The mathematical definition of the Reynolds shear stress is presented in Eq. 1. Physically, the turbulent momentum transport in the flow is represented by the Reynolds shear stress.

$$\overline{uu'} = (U(t) - \overline{U})(W(t) - \overline{W})$$  \hspace{1cm} (1)

Ejection and sweep motions are major contributors to the Reynolds stresses in the region nearer to the wall/surface (Robinson, 1991). The viscous sub-layer contains quasi streamwise vortices; that mainly cause ejections and sweeps (Q2 and Q4, respectively), which contribute to the Reynolds stresses in this region. These near wall shear layers occur when high-speed fluid interacts with low-speed fluid lifted by streamwise vortices. In the buffer region horseshoe vortices begin to form, along with existing streamwise
vortices (Robinson, 1991). In the log and wake regions shear stress is governed by the large scale turbulent structures. In the logarithmic region, three-dimensional structures of the scale of the boundary layer dominate the flow (Adrian et al., 2000, Robinson, 1991).

![Quadrant analysis conventions used in the present work.](image)

**Figure 4: Quadrant analysis conventions used in the present work.**

### 1.3 The shear layer

The shear layer above the street canyon is where the exchange of fluid and pollutants between the canyon and the atmospheric boundary layer occurs. The exchange of momentum also takes place in the shear layer (Blackman et al., 2015, Perret et al. 2016). Canyon flow is highly influenced by how the flow separates from the upstream obstacle and whether the separated shear layer reattaches to that obstacle (Savory et al., 2013). Oke (1988) defined three regimes of flow in urban environments, skimming flow, wake interference flow and isolated roughness flow. An illustration of the different flow regimes is presented in Fig. 5.
The shape of the shear layer depends on the flow regime of the canyon, as do the dynamics of fluid and momentum transport (Oke, 1988). Sallizioni et al. (2011) found that the characteristics of the oncoming boundary layer affect the turbulent flow statistics in the street canyon. They concluded that turbulent transfer was due to the coupling of the overlying boundary layer and shear layer. For example, in a skimming flow regime there is no penetration of the shear layer into the street canyon whilst, in contrast, isolated wake and wake interference regimes do have shear layer penetration (Oke, 1988). Without penetration of the shear layer into the street canyon there is a decoupling of the boundary layer, shear layer and street canyon (Savory et al. 2013). Takimoto et al. (2011) have found that the flapping shear layer generated by shedding correlates with sweep and ejection events, suggesting that ventilation is possibly a function of those events. The unsteady canyon shear layer and its interaction with the large-scale structures above, provides important mechanisms for coupling the flow within the street canyon (Coceal et al., 2007). Kang et al. (2008) found that the depth of the canyon and the momentum thickness of the oncoming boundary layer are important factors in the unsteady dynamics of the shear layer.
1.4 Turbulent structures

Turbulent flow has a wide-range of coherent structures; the smallest at a few times larger than the Kolmogorov scale and the largest, such as in an ABL, which can reach the order of a few kilometres (Takimoto et al., 2013). Although turbulence is a three-dimensional phenomenon, a coherent structure has a large-scale velocity component which is spatially consistent over the structure (Hussain, 1996). The coherent flapping motion of the shear layer generates large-scale turbulent structures, which either shed into the outer flow or penetrate the street canyon (Perret et al, 2013). Perret et al. (2013) show that unsteady fluid exchanges between the canyon and the outer flow are governed by the shear layer. Using Proper Orthogonal Decomposition (POD), they showed a nonlinear interaction between the large-scale structures in the atmospheric boundary and the street canyon. Rough wall flow above buildings has turbulent structures that resemble hairpin vortices rather like those in a smooth wall boundary layer. The shear layers formed over the roughness elements or buildings, generate structures that drive recirculation within a downstream canyon (Coceal et al., 2007). It has been shown that low momentum regions within the cavity are instantaneously correlated with ejections, where low momentum regions are areas where the velocity is lower than the nearby flow (Takimoto et al., 2011,
Ignaki et al., 2012). Coceal et al. (2007) characterized large scale structures as low momentum regions or low speed streaks, which were found to occur frequently in canyon flow. Low momentum regions or low speed streaks could be caused by groups of hairpin vortices. A hairpin vortex consists of a spanwise vortex core above a region of strong $Q^2$ fluctuations ($u' < 0$ and $w' > 0$) and, in boundary layer flow, they are found to be angled at 30-60 degrees to the wall (Adrian et al., 2000). Small packets of hairpin vortices surrounding larger packets of hairpin vortices is a prominent feature of flow in the logarithmic layer (Adrian et al., 2000). A hairpin vortex is often considered to be one of the most important structures in wall turbulence. Hairpin vortices in street canyon flow are generated by strong ejections and then they are rotated and stretched by the mean shear. Hairpin vortices have a significant effect on the strength and frequency of sweep and ejection events which, in turn, ventilate a street canyon (Coceal et al., 2007). Adrian et al. (2000) proposed a packet-structure model which can explain the existence of organized streaky structures generated by hairpin vortices. Packet structures have been found in atmospheric turbulence (Hommena and Adrian., 2003) and their effect on canyon flows is of interest. Takimoto et al. (2013) analysed the similarity of turbulent structures over different urban-like flow regimes in which a two-point correlation method was used to determine the size of turbulence structures. They could identify numerous streaky structures in the lower layer whose length scale increased with height above the ground. In the upper layer, it was found that these streaky structures vanished as height increased. Fig. 7 provides a summary of the turbulent structures present in a street canyon type flow. Referring to Fig. 7, the yellow, green and pink arrows represent the shear layer, $Q^2$ and $Q^4$ events, respectively. The purple regions represent hairpin vortices and the grey regions represent low-momentum regions. The purpose of the schematic in Fig. 7 is to show the complex instantaneous behaviour of a street canyon flow. Ejection events ($Q^2$) contribute to the formation of hairpin vortices, with the sweep ($Q^4$) events moving downwards, away from the hairpins and towards the low-momentum regions below. The role of the shear layer in this mechanism less is known, Salizzoni et al. (2011), Perret and Savory (2013) show that there exists a coupling between the shear layer and the large-scale structures above in the boundary layer. Blackman et al. (2018) investigated the modulation of small scale structures by large scale structures in a street canyon flow.
They found an influence of upstream roughness geometry on the non-linear interactions between the small-scales created by the roughness and the large-momentum regions above. Understanding the interaction between the small-scale structures near roof level of the canyon and the large-scale structures above in the boundary layer and how they drive the process of pollutant transport within the canyon is where a further investigation needs to be conducted.

![Turbulent Structures present in a street canyon flow.](image)

Figure 7: Turbulent Structures present in a street canyon flow. The green arrows and pink arrows represent ejections (Q2) and sweep (Q4) events, respectively. The grey regions represent low momentum regions and the purple regions represent hairpin vortices. The yellow arrows at roof level represents the shear layer.

### 1.5 Experimental considerations

Street canyon flows are studied both experimentally and numerically, and, since the nature of the present work is experimental, the relevant experimental techniques and analysis methods will be reviewed.

In wind tunnel testing three types of scaling similarity exist. Geometric scaling requires that the full-scale and the model have the same ratios between body dimensions. Kinematic scaling consists of geometry and time; matching integral length scales ($L_u / h$)
of turbulence, the boundary layer characteristics such as the roughness velocity \( u_r / U_{ref} = \sqrt{\tau / \rho} / U_{ref} \) where \( \tau \) is the shear stress in the fluid and \( \rho \) is the density of the fluid and \( U_{ref} \) is a mean reference velocity in the boundary layer) and matching the Jensen number \( (Je = h / z_o) \), for example. Finally, dynamic scaling consists of matching the forces. Ideally, for incompressible flows (air can be assumed incompressible for Mach numbers below 0.3), matching the Reynolds number between full-scale and model is required. In wind engineering it is often difficult to simulate the high Reynolds numbers of atmospheric boundary layer flows in wind tunnels. Increasing the Reynolds number allows for the range of turbulent scales be increased. However, for sharp-edged bluff bodies with \( Re > 10^5 \), Reynolds number independence is close to achieved (Yassin and Ohba, 2012). The profile of the approaching boundary layer should be defined from data which are sampled at a high enough frequency, to resolve all the important turbulent scales, and for long enough so that statistically stationary mean velocity profiles and turbulence intensity profiles and turbulence spectra are achieved (Savory et al., 2013).

Particle image velocimetry (PIV) is used in many studies on the dynamics of turbulent street canyon flows (Blackman et al, 2015, Savory et al, 2013, Perret et al. (2016), Takimoto et al., 2011, Salizzioni et al., 2011). The PIV technique consists of a laser sheet illuminating a region of flow seeded with reflective particles. CCD cameras are then used to record images of the illuminated region. The basic two-dimensional PIV technique can yield accurate and high quality instantaneous measurements of flows of gases and liquids ranging from millimetres per second to several meters per second (Adrian, 2005). Particle image velocimetry (PIV) is an optical technique which yields instantaneous velocity measurements. The fluid is seeded with particles which follow the dynamics of the flow (Tropea et al., 2007). A PIV apparatus generally consists of a charge-coupled device (CDD) camera, a laser for illuminating the flow, a synchronizer to control the camera and laser and a computer to record and process the data. Stereo particle image velocimetry (SPIV) was used in the present work to measure the flow field. In SPIV, a second camera is used to add depth-perception. The Sheimpflug condition is a geometric rule that explains the orientation of the plane where the camera is focusing when the lens is not parallel to the measurement plane. If the Sheimpflug condition is satisfied there are
sufficient data contained in the two views to obtain the out-of-plane motion of the particles, such that all three directions can be measured (Tropea et al., 2007). Fig. 8 presents a schematic of a typical SPIV setup. Although, SPIV measurements yield all three velocity components the accuracy of the third component is often less than that of the other two. Despite that, if out of plane motion is small relative to the in-plane components the accuracy of the results increases (Adrian, 2005). For example, an outer plane velocity of 0.15 m/s was found to have an error of 2.7% (Fei and Merzkirch, 2004).

Figure 8: Standard Stereo-PIV setup (Adapted from Bossard et al., 2009).

The experiments in the present work were conducted at the LHEEA atmospheric boundary layer wind tunnel in Nantes, France (a detailed description of the experimental setup can be found in Chapter 2). A simplified street canyon model is studied in the present work. The aspect ratio \(AR = W/h\) of the street canyon is defined as being the ratio between the streamwise width of the canyon \(W\) and the height of the canyon \(h\). A large canyon \(AR\) (\(1.5 \leq AR \leq 3\)) results in a wake-interference flow and a small \(AR\) (\(AR \leq 1.5\)) results in a skimming flow regime. Finally, a street canyon with \(AR \geq 3\) results in an isolated-roughness flow, Oke, 1988 (refer to Fig. 5 for a diagram of the different
flow regimes). The planform packing density ($\lambda_p$) is defined as being the ratio between the total plan area ($A_d$) and the total plan area of the obstacles ($A_p$). Fig. 8 provides an example of modelling urban environments in wind tunnels and Fig. 9 presents the upstream roughness arrays used in wind tunnel experiments. Full-scale field experiments have been conducted, using experimental techniques such as sonic anemometers (Blackman et al., 2015b) however, due to the random nature of the wind, it is often difficult to obtain the desired flow regime. The advantage of wind tunnel experiments is that the upstream boundary layer can be controlled. For example, the wind direction and velocity can be fixed. In wind tunnel experiments model scaling is an important factor which is often overlooked. The physics occurring within the canyon are highly sensitive to the approaching boundary layer but, unfortunately, many street canyon flow wind tunnel experiments have not been representative of full-scale boundary layers found in the atmosphere. The non-dimensional parameters of $L_u / h$ and $z_o / h$ between the wind tunnel model and full-scale should be matched between 2-3 to guarantee that the terrain is the same for both cases (Savory et al., 2013).

Figure 9: The experimental modelling of an urban street canyon.
Figure 10: Upstream roughness arrays a) two-dimensional rectangular bars. b) three-dimensional staggered cube roughness

1.6 Motivation

A knowledge gap exists, in that there is information missing on the spanwise structure of the turbulence in street canyon flows. The spanwise structure of the flow is important to understand the mechanisms between the lower-atmosphere and the street canyon flow. There is an abundance of information about how the flow behaves in the vertical direction in street canyon flows. To the best of the present author’s knowledge there has not been a systematic study of the flow in a horizontal plane at canyon rooftop level. Conducting measurements in a horizontal plane near roof level allows us to gain valuable experimental data that can be used to validate unsteady numerical simulations, for example their ability to correctly reproduce the statistical features of the instantaneous coherent structures responsible for the transport of a large fraction of the momentum. The reasoning behind the location of the measurement plane is that the interactions between the shear layer and the large-scales above in the boundary layer take place near roof level.
Hence, a large amount of fluid exchange between the canyon and the boundary layer above takes place here, making this region of great interest.

## 1.7 Objectives of the thesis

The present work will investigate the effect of roughness and canyon aspect ratio on the mean turbulent statistics, integral length scales, sweep/ejection events and turbulent structures in a simplified street canyon flow. The main objectives of this thesis are:

a) To strengthen the understanding of the 3D flow behaviour in a street canyon by characterizing the spanwise turbulence at roof-level, by investigating the effect of roughness and canyon aspect ratio on the mean turbulence statistics and integral length-scales.

b) To explore the flow structures and mechanisms of the turbulent momentum transport and to investigate the interaction between the small-scales of turbulence generated by the roughness and the large-scales present in the boundary layer above.

## 1.8 Scope of the thesis

In the present work six experimental configurations were studied: two canyons with three upstream roughness configurations. The aspect ratios of the two street canyons, with $AR = 1$ and 3, are denoted as C1h and C3h, respectively. The upstream roughness conditions consisted of a staggered cubical array ($\lambda_p = 25\%$, denoted as Rcu) or 2D square cross section rectangular bars with a spacing of $1h$ or $3h$ ($\lambda_p = 25\%$ and $\lambda_p = 50\%$, denoted as R1h and R3h, respectively). For example, a configuration consisting of a street canyon with of $AR = 1$ and a 3D staggered cube upstream roughness would be denoted as C1hRCu. The height of the cubes and 2D bars was also 50 mm. Stereoscopic PIV measurements were conducted in the horizontal plane located at a height of $0.90 +/- 0.05h$ and aligned with the free stream flow. A pitot-static tube located at $x = 15$ m, $y = 0$
m, $z = 1.5\, \text{m}$ was used to measure the dynamic pressure from which the velocity was set to be $U_e = 5.9\, \text{m s}^{-1}$, in all the experiments, giving a Reynolds number of $1.9 \times 10^4$, based on this velocity and the canyon height, $h$ (Blackman et al., 2015). All experiments were conducted with the flow being perpendicular to the spanwise axis of the street canyon, this being only flow direction studied.

### 1.9 Organization of the thesis

The following chapters are comprised of two articles which introduce and discuss the research conducted. The first article (Ch. 2) is an investigation of the spanwise variation of roof-level turbulence in a street canyon flow. To achieve this simplified wind tunnel models were used to study the turbulent statistics for a range of configurations. The second article (Ch. 3) is an examination of the spanwise quadrant events in a street canyon flow, where various analysis techniques were used to study the large- and small-scales of the turbulence. The final section (Ch. 4) draws conclusions from the present work, provides suggestions for future work and discusses the insights that the current research conveys into further understanding of the fluid mechanic mechanisms of ventilation in street canyon flows.

### 1.10 Summary

The present chapter provided a general literature review explaining street canyon flows. The experimental methodology used in this field was summarized, including the techniques used in the present work. Finally, the objectives and the purpose of this thesis were explained.

Air quality in urban environments is an important issue in present times (WHO, 2014). Thus, it is of great importance to understand physical processes that govern the dynamic transport of air and pollutants in an urban environment. In street canyon flows the oncoming boundary is generated by an upstream array of roughness elements and how
this boundary layer interacts with the street canyon is the broad focus of this work. Quadrant analysis can be used to identify sweep and ejection events (denoted as Q4 and Q2, respectively), these events are responsible for the exchange of pollutants between the street canyon and the oncoming boundary layer. When the oncoming boundary layer interacts with the street canyon, a shear layer is generated. The flapping shear layer generated by vortex shedding correlates with sweep and ejection events. The shear layer region is where the exchange of fluid and pollutants between the canyon and the atmospheric boundary layer occurs. The large-scale structures present in the boundary layer interact with the shear layer, which, in turn, governs the pollutant transport in the street canyon.

In the next chapter, the effect of upstream roughness and canyon AR on the mean turbulent statistics, two-point correlations and integral length scales at roof-level in a street canyon flow will be presented.

1.11 References


Savory E, Perret L, Rivet C (2013) Modelling considerations for examining the mean and unsteady flow in a simple urban-type street canyon. Meteorol Atmos Phys 121: 1–16


Chapter 2

The spanwise variation of roof-level turbulence in a street canyon flow

The present chapter investigates the effect of upstream roughness and canyon width on turbulent street canyon flow. Measurements in a horizontal plane were conducted at near roof-level of a street canyon using Particle Image Velocimetry in a wind tunnel. Three upstream roughness arrays and two canyon width ($W$) to height ($h$) aspect ratios ($AR = W/h = 1$ and 3) were investigated. The arrays consisted of three-dimensional (3D) cubes (plan area density, $\lambda_p = 25\%$), 1$h$ spaced two-dimensional (2D) bars (skimming flow, $\lambda_p = 50\%$) and 3$h$ spaced 2D bars (wake interference flow, $\lambda_p = 25$). Understanding the spanwise structure of the flow and how it interacts with large scale structures is necessary to reliably predict the mean pollutant transport in the lateral direction along the canyon and to further develop our knowledge on the 3D behaviour of turbulent street canyon flows. However, to the author’s knowledge there has not previously been a systematic study of the flow in a horizontal plane at canyon rooftop level. The mean turbulent statistics are presented, whilst two-point correlations and integral length scales are computed for the different configurations. The results show a significant effect of upstream roughness on these quantities. The total turbulent kinetic energy and shear stress are found to be highest for the wake interference flow regimes and lowest for the
skimming flow regimes. It is found that the 3D upstream roughness configurations result in a significantly weaker correlation in the spanwise direction at canyon roof level. A similar trend is observed in the spanwise integral length scales. The shear layer thickness is found to be related to the magnitude of the correlations near roof-level of the street canyon.

2.1 Introduction

Air quality in urban environments is a critical issue in contemporary times with the resulting socioeconomic implications being of great concern. Pollution in the Earth’s atmosphere leads to human death, disease and harm to our natural resources (World Health Organization, 2014). Understanding the urban climate is challenging due to the high geometrical complexity of built areas and the existence of numerous interacting thermodynamic processes where the wind field and turbulence play a crucial role in determining the instantaneous dynamics of the flow. In particular, the high Reynolds number atmospheric flow combined with the geometric complexity of the urban canopy present strong multi-scale characteristics, both spatially and temporally. Understanding the spatial structure of such a flow is, therefore, important, particularly if one aims to investigate unsteady phenomena such as an accidental release of pollutant or flow-state prediction from a limited number of sensors.

The rectangular street canyon model is a simplified representation of many urban street configurations and the effects of canyon aspect ratio $AR$ (streamwise width $W$ / canyon height $h$) and upstream roughness on street canyon flow has been well studied. Grimmond and Oke (1999) defined three flow regimes in urban environments; skimming flow, wake interference flow and isolated roughness flow. They found that the plan area packing density (the ratio of plan area of the roughness obstacles to the total plan area, denoted as $\lambda_p$) of the upstream roughness and whether it was 2D or 3D had an impact on the flow within the canyon. Experimental wind tunnel studies on street canyons frequently use Particle Image Velocity (PIV) to measure the flow field, and mostly conduct measurements in a single vertical plane, see Salizzoni et al. (2011), Savory et al.
When studying this configuration in a wind tunnel, Savory et al. (2013) noted that it is crucial to match the roughness length \((z_0)\) and the integral length scale \((L_{uu})\) within factors of two to three to ensure that full and model scales are matched properly. It was also noted that the geometry of the upstream roughness significantly affects the structure of the oncoming boundary layer, where 3D roughness is found to generate 3D turbulent structures that resemble those in a more realistic boundary layer found in an urban environment. Suggestions by Savory et al. (2013) have been employed in the present work. The effect of roughness and canyon geometry on the mean turbulent statistics and structures in the spanwise direction is essential to understanding local instantaneous pollutant transfer between street canyons and the overlying atmospheric boundary layer. The main objective of the present study is to investigate the streamwise and spanwise statistical flow structure in a horizontal plane located near roof-level, where this exchange takes place.

The upstream roughness significantly affects one-point statistics within and above the street canyon. Blackman et al. (2015) found a significant effect of \(\lambda_p\) on the mean streamwise velocity, shear stress, turbulence intensity and integral length scales, based on vertical profiles. It was found that the mean streamwise velocity immediately above the canyon for, configurations of the same \(\lambda_p\), is higher for the 3D upstream roughness than the 2D roughness and that the spatially averaged shear stress is lower in 3D than 2D configurations. Blackman et al. (2015) also found that the integral length scale was larger for the 2D case than the 3D case when \(\lambda_p\) was the same and that decreased ventilation was found to occur in the skimming flow regime. Cheng et al. (2007) showed that the shear stress is dependent on \(\lambda_p\) for aligned upstream roughness cases and not significantly dependent on \(\lambda_p\) above the height of the roughness elements. However, Kanda et al. (2004) found that turbulent statistics were affected by \(\lambda_p\) inside and near the roughness and shear layer. Salizzoni et al. (2011) found that the characteristics of the oncoming boundary layer influence the turbulent flow statistics in the street canyon, with the shear stress being dependent on \(\lambda_p\). The effect of the roughness on the shear stress was observed within the street canyon and persisted up to a height of 5\(h\). They concluded that turbulent transfer was due to the coupling of the overlying boundary layer and shear layer and that
the structure of the external flow influences that of the canyon flow. They also noted that the turbulent structures and turbulence intensity found in the wake interference regime were larger than in the skimming flow regime above the roughness elements. Marciotto and Fisch (2013) found that canyons with a higher value of $AR$ had a higher shear stress, which was previously noted by Salizzoni et al. (2011).

Canyon geometry and the upstream roughness influence the turbulent structures in the flow that, in turn, relate to pollutant transport. Nosek et al. (2017) found that pollutant transport strongly depends on the roof arrangement. It was found that the higher the upstream wall of the street canyon the greater the pollutant removed through the canyon. Finally, Nosek et al. (2017) also found that lateral coherent structures correlate with the lateral ventilation process. Blackman et al. (2015) found that the thickness of the shear layer is affected by the $AR$ of the canyon and the upstream roughness. Perret and Savory (2013) showed that unsteady fluid exchanges between the canyon and the outer flow are governed by the shear layer. Using Proper Orthogonal Decomposition (POD), they showed a nonlinear interaction between the large-scale structures in the atmospheric boundary layer and the street canyon. Blackman et al. (2018) found that there is an influence of upstream roughness geometry and $\lambda_p$ on the non-linear interactions between large-scale momentum regions and the small-scales generated by the roughness, with the non-linear relationship for the wake interference flow regime being significantly different from the skimming flow regime.

Turbulence is a 3D phenomenon and, thus, to understand turbulent street canyon flow properly one must investigate how the flow behaves in both the spanwise ($y$) direction and the vertical ($z$) direction. Studies by Watanabe (2004), Raupach et al. (1996) and Shaw et al. (1995) were conducted for vegetation canopies. Shaw et al. (1995) conducted a wind tunnel study of air flow over waving wheat. Two-point, space-time correlations of streamwise ($x$) and vertical velocity components were computed from the wind tunnel simulation of an atmospheric boundary layer, with the wheat canopy model constructed of flexible nylon stalks. It was concluded that it was not appropriate to apply the Taylor hypothesis of frozen turbulence in the region of the canopy and, therefore, the integral length scales were computed directly from two-point statistics. It was also found that the
lateral integral length scales were smaller than those computed in the streamwise direction by factors ranging from 1.9 to 4.2. Raupach et al. (1996) stated that the approach of applying the Taylor hypothesis is fraught with difficulty as high turbulence intensities \( (u'/\bar{U} > 1) \), where \( u' = U - \bar{U} \) is the fluctuating velocity) are present within the canopy. Raupach et al. (1996) conducted two-point correlations of various model and field canopies in the \( x-z \) and \( y-z \) planes. In the \( x-z \) plane the streamwise fluctuating velocity correlation produced nearly elliptical stretched correlation contours, with a tilt angle of approximately 18 degrees, an effect that was reported to diminish within the canopy. Shaw et al. (1995) suggested that this more rapid reduction of correlation within the canopy is due to the creation of small scale motions and the breakdown of large scale flow by canopy elements. In contrast, the correlation of the vertical fluctuating velocity revealed nearly circular correlation contours and was found to decay much more rapidly with spatial separation. The correlations in the \( y-z \) plane produced contours which were nearly circular for both the streamwise and vertical fluctuating velocities. Raupach et al. (1996) concluded that, in a time-averaged sense, fluid motions near the top of the canopy are well correlated over length scales of the order of the height of the canopy, \( h \). It was also suggested that zones where the sign of the correlation reverses could be a direct consequence of the formation of dominant flow structures, Shaw et al. (1995). In a field experiment Inagaki et al. (2009) conducted multi-point measurements (3D velocities and temperatures) in a cubical array using multiple sonic anemometers aligned at equal heights in the streamwise and spanwise directions. Using two-point correlations, they reported that the correlation of the fluctuating streamwise velocity \( (u') \) was higher along the streamwise direction than for an equal magnitude of spanwise separation. The result was attributed to the existence of coherent structures elongated along the streamwise direction and it was postulated that the coherent structure of \( u' \) is geometrically similar irrespective of the type of roughness.

Takimoto et al. (2013) used PIV to study the turbulent flow fields in horizontal cross-sections of a smooth wall and above the roughness elements of a variety of rough walls. The size of the turbulent structures was quantified using a two-point correlation method. They found that the length and shape of large-scale structures were highly correlated with
the velocity gradient for each measurement height. Small-scale structures demonstrated weak dependency on the velocity gradient. From snapshots of instantaneous flow fields, they found differences in small scale structures from case-to-case. Structures of organized motions were reported to resemble each other, agreeing with the two-point correlations. The findings from Takimoto et al. (2013) show that it is useful to understand how the flow behaves in the spanwise direction as large scale turbulent organized structures were found to be related to the vertical velocity gradient and boundary layer thickness, while small-scale structures had a weak dependency on the vertical velocity gradient and boundary layer thickness. Takimoto et al. (2011) suggested that flushing motions (characterized by a large-scale upward motion) are correlated with large-scale low momentum regions passing over the canopy, spanwise information about the flow can also provide insight on the spanwise structure of these flushing events. Michioka et al. (2014) conducted Large Eddy Simulations (LES) of multiple 3D urban array configurations. They found, when studying 3D arrays for smaller lateral aspect ratio (LAR, defined to be the building length to height ratio) configurations that the contribution of turbulent mass flux to net mass flux at roof level was closer to unity than for larger lateral aspect ratio configurations, indicating that pollutant removal near canyon roof level is mainly driven by turbulent motions. Increasing the LAR caused the relative contribution of turbulent mass flux to net mass flux to decrease. However, for an infinite LAR street canyon (i.e. a 2D street canyon) the relative contribution reached unity due to lowered lateral flow convergence. Volino et al. (2009) analysed the structure of turbulence in a boundary layer with 2D roughness (which consisted of evenly spaced rectangular bars), and they were able make definitive conclusions regarding correlations and integral length scales. They found that the streamwise extent of the vertical fluctuating velocity correlation is considerably less than that of the fluctuating streamwise velocity correlation. This was explained by the fact that the streamwise correlation is related to the convection velocity of hairpin packets in the boundary layer. The streamwise to spanwise ratio of the integral length scales for the vertical velocity component ($\frac{L_{ww,x}}{L_{ww,y}}$ using the conventions in this work where $L_{ww,x}$ would be the streamwise integral length scale of the vertical turbulent velocity) was found to be 0.8 for smooth and 3D rough walls. It was found that in the outer layer the streamwise and wall-
normal length scales are essentially equal for smooth and 3D rough wall flows and an average of 35% and 40% larger for 2D rough walls for $L_{ww,x}$ and $L_{ww,y}$, respectively.

Understanding the 3D urban wind dynamics will assist in developing a model for predicting pollutant transport and air quality in the urban environment. Experimental results can be used to validate unsteady numerical simulations, for example their ability to correctly reproduce the statistical features of the instantaneous coherent structures responsible for the transport of a large fraction of the momentum.

The spanwise structure of the flow is important to understand the mechanisms between the lower-atmosphere and the street canyon flow. As mentioned above, there is an abundance of information about how the flow behaves in the vertical direction in street canyon flows. What lacks is information in the spanwise direction. To the best of the present author’s knowledge there has not been a systematic study of the flow in a horizontal plane at canyon rooftop level. The effect of the upstream roughness and canyon geometry on the mean turbulent statistics near roof-level in the horizontal plane is investigated in this work. The questions to be addressed in the present study are:

a) What is the impact of 2D versus 3D arrays and $\lambda_p$ on the time-averaged mean turbulent statistics in a horizontal plane near roof-level of a canyon?

b) What is the impact of 2D versus 3D arrays and $\lambda_p$ on two-point correlations and integral length scales in the streamwise and spanwise directions in a horizontal plane near roof-level of a canyon?

c) What are the implications on the time-averaged mean structure of the flow at this location of the street canyon?

The objective is to establish how the oncoming boundary layer flow interacts with the street canyon over a range of configurations. The flow is investigated in the spanwise direction to complement Blackman et al. (2015), who characterized the vertical plane. The correlations and scales of turbulence will also be investigated to further understand the dynamics of the flow and structure of turbulence in the spanwise direction. The present results provide a clearer picture on the nature of 3D turbulent flow in street canyons. Section 2.2 outlines the experimental setup and details used in the present work.
Afterwards, Sect. 2.3 presents the results and discussion, which demonstrate the effects of canyon AR value and upstream roughness on the mean turbulent statistics, two-point correlations and integral length scales. Finally, this section is followed by a summary and conclusions.

2.2 Experimental details

The experiments were conducted in the low-speed, suck-down boundary layer wind tunnel in the Laboratoire de recherché en Hydrodynamique, Énergétique et Environnement Atmosphérique at École Centrale de Nantes, France. The Boundary layer development was initiated by five 800 mm high vertical tapered spires located immediately downstream of the contraction and a 200 mm high solid fence across the working section positioned 750 mm downstream of the spires. After the spires a 13 m fetch of staggered cubes was employed, followed by staggered cubes, 1h or 3h spaced bars. The street canyon flow measurements were taken 5.5 m downstream of this initial development region. The dimensions of the wind tunnel working section were 2 m (width) × 2 m (height) × 24 m (length) and the wind tunnel had a 5:1 ratio inlet contraction. The change of roughness from staggered cubes to 1h or 3h bars was found to be negligible and the development of the internal boundary layer was found to reach equilibrium by the measurement region (Blackman et al., 2015). Two canyon aspect ratios were studied for three upstream roughness conditions. The street canyon was constructed using two square cross section rectangular bars with a height of 50 mm (h) and a lateral length of 1500 mm (L/h = 30). Savory et al. (2013) demonstrated that the centre-line mean flow profiles were independent of the canyon length when L/h > 9. Six flow conditions were studied: two canyons with three upstream roughness configurations. Street canyons of AR = 1 and 3 are denoted as C1h and C3h, respectively. The upstream roughness conditions consisted of a staggered cubical array (λp = 25%, denoted as RCu) or 2D square cross section rectangular bars with a spacing of 1h or 3h (λp = 25% and λp = 50%, denoted as R1h and R3h, respectively). For example, a configuration consisting of a street canyon with of AR = 1 and a 3D staggered cube upstream roughness would be
denoted as C1hRCu. The height of the cubes and 2D bars was also 50 mm. It should be noted that the experimental conditions in this present work are the same as in Blackman et al. (2015, 2018). A schematic of the experimental setup can be found in Fig. 11.

Figure 11: Stereoscopic PIV set-up (left), top view of PIV set-up (right). where • denotes the reference point is located at \((x = 0, \ y = 0, \ z = 0.9h)\), wind tunnel set-up (bottom).

Stereoscopic PIV measurements were conducted in the horizontal plane located at a height of 0.90 +/- 0.05h and aligned with the free stream flow. This height was verified by comparing turbulent statistics to those from Blackman et al. (2015) which consisted of measurements in the vertical plane (see Sect. 2.3.1). The PIV setup was located beneath the wind tunnel floor and images were taken through a glass floor. The final spatial resolution of the vector fields was 1.6 mm \((0.032h)\) in both \(x\) and \(y\) directions, and a
temporal sampling frequency of 7 Hz was used. The fields of view were $1h \times 6h$ and $3h \times 6h$ for the $1h$ and $3h$ canyons, respectively. A Litron double cavity $2 \times 200$ mJ Nd-Yag laser was used to illuminate the measurement region. The flow was seeded with glycol/water droplets (average diameter of 1 µm) via a fog generator. DANTEC Dynamic Studio software was used to synchronize the camera and laser, as well as for the calculation of the PIV vector fields. A FFT two-component PIV algorithm with sub-pixel refinement was used in the vector field computations. An iterative cross-correlation analysis was performed which consisted of an initial window size of $64 \times 64$ pixels with a final interrogation window of $32 \times 32$ pixels and the overlap of the analysis window was 50%. A pulse interval of 500 µs was used in the computation of the velocity vector fields. The uncertainty in the measurements was approximated by the maximum standard deviation of the PIV statistics due to statistical error. They were estimated by assuming Gaussian velocity distributions and normalized by the corresponding local statistic. They were found to be 0.86%, 1.41% and 3.92% for the mean velocity, standard deviation and turbulent shear stress, respectively. The statistical error was computed using 2551 independent samples (out of 10000 samples recorded) where independent samples is the number of samples that are separated by a of period two times the integral time scale. Refer to Appendix-C for further details on the error analysis. A pitot-static tube located at $x = 15$ m, $y = 0$ m, $z = 1.5$ m was used to measure the dynamic pressure from which the velocity was set to be $U_e = 5.9$ ms$^{-1}$, this velocity was used for all the experiments in this present work giving a Reynolds number of 1.9 x 10$^4$, based on this velocity, and canyon height, $h$ (Blackman et al., 2015). A summary of the configurations can be found in Table 1. The oncoming boundary layer conditions are presented in Table 2.

In the present work, the instantaneous velocities in the $x$, $y$ and $z$ directions are the streamwise ($U$), spanwise ($V$) and vertical ($W$) components, respectively. Time averaging is denoted by an overbar, the time-averaged mean velocity, $\overline{U}$, is defined as $\overline{U} = U(t) - u'(t)$ based on the Reynolds decomposition, $U(t)$ denotes the instantaneous velocity and $u'(t)$ the velocity fluctuation from the mean. The standard deviation is defined as $\sigma_u = \sqrt{\langle (U(t) - \overline{U})^2 \rangle}$. The 3D turbulent kinetic energy is defined as $\text{TKE} = 0.5(\sigma_u^2 + \sigma_v^2 + \sigma_w^2)$. 
Table 1: Canyon and roughness configurations studied in the present work.

<table>
<thead>
<tr>
<th>FLOW</th>
<th>Roughness:</th>
<th>Roughness:</th>
<th>Roughness:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>25% Staggered cubes</td>
<td>2D bars, spacing: 1h</td>
<td>2D bars, spacing: 3h</td>
</tr>
<tr>
<td></td>
<td>((Rcu) \lambda_p = 25%)</td>
<td>((R1h) \lambda_p = 50%)</td>
<td>((R3h) \lambda_p = 25%)</td>
</tr>
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<td>Canyon: Width=1h</td>
<td><img src="c1hRcu.png" alt="Image" /></td>
<td><img src="c1hR1h.png" alt="Image" /></td>
<td><img src="c1hR3h.png" alt="Image" /></td>
</tr>
<tr>
<td>Canyon: Width=3h</td>
<td><img src="c3hRcu.png" alt="Image" /></td>
<td><img src="c3hR1h.png" alt="Image" /></td>
<td><img src="c3hR3h.png" alt="Image" /></td>
</tr>
</tbody>
</table>

Table 2: Oncoming boundary layer characteristics. \(u^*\) denotes friction velocity, \(d\) denotes the displacement height and \(z_o\) denotes the roughness length. (Blackman et al., 2015)

<table>
<thead>
<tr>
<th>Roughness</th>
<th>(\lambda_p)</th>
<th>(u^*/U_e)_{Spatially Averaged (x)}</th>
<th>(u^*/U_e)_{Spatially Averaged (x)}</th>
<th>(d/h)_{Spatially Averaged (x)}</th>
<th>(d/h)_{Spatially Averaged (x)}</th>
<th>(z_o/h)_{Spatially Averaged (x)}</th>
<th>(z_o/h)_{Spatially Averaged (x)}</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rcu</td>
<td>25</td>
<td>0.066</td>
<td>0.064</td>
<td>0.892</td>
<td>0.900</td>
<td>0.061</td>
<td>0.060</td>
</tr>
<tr>
<td>R1h</td>
<td>50</td>
<td>0.047</td>
<td>0.049</td>
<td>0.980</td>
<td>0.927</td>
<td>0.008</td>
<td>0.015</td>
</tr>
<tr>
<td>R3h</td>
<td>25</td>
<td>0.072</td>
<td>0.070</td>
<td>0.522</td>
<td>0.725</td>
<td>0.143</td>
<td>0.125</td>
</tr>
</tbody>
</table>
2.3 Results and discussion

2.3.1 Comparison with previous data sets

In this section, the mean turbulent statistics are compared to those of Blackman et al. (2015), which were taken in a vertical ($x$-$z$) plane on the centreline ($y = 0$) of the canyon. The purpose of this analysis is to determine the precise height at which the light sheet was positioned and to assess the extent of the agreement between the two experiments. It is important to know the precise vertical position of the measurement region as Blackman et al. (2015) found that the mean turbulent statistics change significantly with height near canyon roof-level. The time and spanwise spatially averaged profiles of the statistics are presented in Figs. 12 and 13 for the C1hR3h and C3hR3h configurations, respectively. The bars on the present data represent the spanwise standard deviation of the given statistic. Results from Blackman et al. (2015) at vertical positions ranging from $0.83h$ to $0.93h$ are compared with the present data. Based on this comparison it is estimated that the horizontal plane in the present work is located at approximately $z/h = 0.9$, with an uncertainty of approximately $\pm 0.05h$. A possible source of error which should be considered is that the vertical velocities in the present work are computed from reconstructed SPIV images, whereas in Blackman et al. (2015) the reconstructed component was the spanwise velocity.
Figure 12: A comparison of the time and spatially averaged turbulent statistics for the C1hR3h configuration of the present work and Blackman et al. (2015). a) Mean streamwise velocity; b) Mean vertical velocity; c) Reynolds shear stress; d) Turbulent kinetic energy. The error bars represent the spanwise ($y$) variation of the given statistic.
Figure 13: A comparison of the time and spatially averaged turbulent statistics for the C3hR3h configuration of the present work and Blackman et al. (2015). a) Mean streamwise velocity; b) Mean vertical velocity; c) Reynolds shear stress; d) Turbulent kinetic energy. Line colours are the same as in Fig. 12. The error bars represent the spanwise (y) variation of the given statistic.

2.3.2 Mean turbulent statistics

In the following section the effect of roughness on the mean turbulent statistics is presented. Plots of the mean streamwise velocity, mean vertical velocity and Reynolds shear stress for all configurations are presented in Fig. 14. The profiles in Fig. 14, are time and spatially averaged across the width of the canyon and the bars represent the spanwise standard deviation. It can be observed that the mean streamwise velocity is highest for the skimming flow regime case (R1h), larger than both the wake interference (R3h) and 3D (Rcu) cases. Although Blackman et al. (2015) found the same trend, with the skimming flow regimes yielding the highest values, in the present work, for the same
The 3D configurations yield smaller streamwise velocities than the 2D configurations. This inconsistency with Blackman et al. (2015) is because in the present work the velocity profiles are plotted along $x$ and are at a fixed height ($z$), whereas in their work the velocity profiles are plotted in the centre of the canyon ($x=0$) and along $z$. Kanda et al. (2004) and Salizzoni et al. (2011) found that the magnitude of mean streamwise velocity depends on $\lambda_p$ for 2D cases and this is confirmed in the present results for both streamwise and vertical velocities. The vertical velocities were found to be lower for C1h than the C3h configurations, equalling zero at the streamwise position of $x = 0$, for the C1h configurations. The shear stress was found to be higher for the wake interference configurations (R3h). The $\lambda_p$ was found to affect the magnitude of the shear stress for 2D configurations for both canyons. The 3D configurations (Rcu) were found to have higher shear stresses than the skimming flow cases (R1h), which were found to have the lowest shear stresses. The trend of higher $AR$ having a larger shear stress was noted by Blackman et al. (2015), Michioka and Sato (2012), and Salizzioni et al. (2011). However, the present results contradict those found in Mariotto and Fisch (2013), who found that $\lambda_p$ did not influence the shear stress. This inconsistency can be explained by the fetch used in their experiment not being long enough to allow for a sufficiently turbulent boundary layer to develop.
Figure 14: Time and spatially averaged turbulent statistics for the C1h and C3h configurations a) Mean streamwise velocity, C1h; b) Mean streamwise velocity, C3h; c) Mean vertical velocity, C1h; d) Mean vertical velocity, C3h; e) Reynolds shear stress, C1h; f) Reynolds shear stress, C3h.
The 3D turbulent kinetic energy (TKE), time and spatially averaged across the width of the canyon, is presented in Fig. 15. It is found that the wake-interference flow regimes (R3h) have the largest energy levels, with the 3D (Rcu) and skimming flow (R1h) cases following in descending order. Blackman et al. (2015) found that in the shear layer ($z/h = 1$) the highest contribution to the 3D TKE was by the streamwise component, with its contribution to the total TKE decreasing with height. This is also found in the present results (not shown here). The $\lambda_p$ has a significant effect on the TKE profiles at near-roof level. For 2D flows (R1h and R3h configurations) it can be concluded that the lower the $\lambda_p$, the lower the TKE. The 2D flow configurations were found to have higher values of TKE than 3D flows for the same the $\lambda_p$. A similar trend was found in the shear stress profiles.

![Figure 15: 3D Turbulent kinetic energy, spatially averaged in the streamwise direction a) C1h configurations; b) C3h configurations](image)

2.3.3 Two-point statistics

Two-point space and time fluctuating velocity correlations offer important information regarding the structure of the flow field which single point measurements cannot provide. A two-point spatial correlation was conducted using the middle of the street canyon ($x_{ref} = 0h$, $y_{ref} = 0h$) as the reference point. The two-point correlation coefficient was computed using Eq.2.
\[ R_{uu}(x_{ref}, y_{ref}, x, y) = \frac{u'(x_{ref}, y_{ref})u'(x, y)}{u'^2(x_{ref}, y_{ref})u'^2(x, y)} \]  

(2)

Contours of the correlation fields are presented in Figs. 15 and 16 for 1\( h \) and 3\( h \) canyon widths, respectively. Plots of the correlations along the \( x \) and \( y \) centrelines for streamwise \( (u') \), spanwise \( (v') \) and vertical \( (w') \) fluctuating velocities (with \( x_{ref} = 0h, y_{ref} = 0h \) set as the reference point) can be found in Figs. 17 and 18. It can be observed that the correlation is symmetrical for all quantities in the spanwise direction, confirming the spanwise homogeneity of the present flow configurations. Symmetry in the \( y-z \) plane for correlations of spanwise and vertical velocity fluctuations was also observed by Shaw et al. (1995) and Raupach et al. (1996). Raupach et al. (1996) noted that the correlation contours were roughly circular with a radius of 0.8\( h \). Within Figs 15 and 16, the effect of roughness on the flow can be seen qualitatively. The effect of roughness is more prominent in C1h than C3h configurations. The structure of the correlation is more elongated in the streamwise direction and is narrower for C3h. Takimoto et al. (2013), Watanabe (2004) and Shaw et al. (1995) also found elongated correlation structures in the streamwise direction. The opposite is true for C1h, with the structure of the correlation elongated in the spanwise direction. Shaw et al. (1995) attribute this to the presence of longitudinally elongated structures in the boundary layer and, from the present results it can be observed that these structures are only present in the C3h configurations. It can be concluded that \( AR \) significantly influences the shape of the correlation, in the C1h configurations there appears to be a “squashing” effect imposed on the correlation by the canyon geometry, whereas in the C3h configurations this is not present. For the C1h canyons the largest circular radius of the correlation (region of the correlation field which is circular) was 0.3\( h \) for the C1hR3h configuration, whilst for C3h the largest radius was found to be approximately 0.3\( h \) for C3hR3h. This suggests that the size of the circular radius of the correlations is independent of canyon geometry and only depends on the roughness (other configurations had smaller circular correlation radii, all within 0.1\( h \)-0.2\( h \) for both R1h and Rcu). Although the circular correlation radii are smaller than those
found by Raupach et al. (1996), this could be attributed to the different flow regimes (flow over a model wheat field) and the measurement region being higher ($z = 1h$ versus $0.9h$ in the present work). The circular radii in the correlations suggest that the small-scales are rather isotropic and that their size depends on the upstream roughness configuration. Referring to the correlation contours (Figs. 16 and 17) the regions corresponding to high correlation levels (0.8 - 0.9) are almost circular, indicating that small-scale structures are isotropic. At lower level of correlation, the contours are deformed by the presence of the canyon walls that limits the streamwise extent of the flow, while larger length scales are found in the spanwise direction, with a dependence on the flow configuration.

![Figure 16: Two-point correlation fields, $R_{uu}$ a) $C_{1hRcu}$; b) $C_{1hR1h}$; c) $C_{1hR3h}$. Reference point located at $(x=0h, y=0h)$. Contour increments of $R_{uu}$ are 0.1.](image)

Perret et al. (2016) studied a street canyon with $AR = 0.7$ (skimming flow regime, $W/h < 1.5$) and found that the spanwise component is especially effected by large scale fluctuations of low temporal frequency. They found large scale organization of the flow
with coherent motions often spanning the whole cross-section of the street canyon. In the present work, the correlations found to have a strong spanwise structure, especially in the streamwise component for the C1h canyons, suggesting large-scale spanwise flow organization. The canyon studied in Perret et al. (2016) and in the present work the C1h canyons were found to have stronger correlations than the C3h canyons. It appears that in canyons with smaller $AR$ (particularly those which are classified to be in the skimming flow regime) have large-scale organization in the spanwise direction, based on their correlation strengths. The spanwise structure of flushing events proposed by Takimoto et al. (2011) could also be affected by the upstream roughness. Referring to Fig. 20, the $R_{uu}$, $R_{vv}$, and $R_{ww}$ correlations lengths are larger for the R3h upstream roughness configuration, this could suggest that a wake-interference flow regime could be linked to larger spanwise flushing events in the street canyon.
Figure 17: Two-point correlation fields, $R_{uu}$. a) C3hRcu; b) C3hR1h; c) C3hR3h. Reference point located at $(x=0h, y=0h)$. Contour increments of $R_{uu}$ are 0.1.
Raupach et al. (1996) arbitrarily defined a “significant correlation” to be \( R_{uu} > 0.2 \) at height \( h \). Using that definition and referring to Figs. 16, 17, 18 and 19 it can be found that for the C1hR1h and C1hR3h configurations there is a significant \( R_{uu} \) correlation for the entire spanwise width of the canyon (-3\( h \) to 3\( h \)). The C1hRcu configuration shows a significant spanwise \( R_{uu} \) (denoted as \( R_{uu,y} \) from here on) correlation which is approximately 50\% smaller than the C1hR1h and C1R3h configurations. It is also observed that \( \lambda_p \) does not seem to affect the spanwise correlation for the C1h configurations. For the C3h configurations the effect of roughness on the \( R_{uu} \) correlations is less strong. The strength of the \( R_{uu,y} \) correlations for the 3D roughness cases (RCu) remain approximately the same (relative to the 2D roughness cases, R1h and R3h) when the \( AR \) is increased. It can be concluded that spanwise correlations decay much more rapidly for flows with 2D roughness arrays when \( AR \) is increased. The smallest \( R_{uu,y} \) correlation for C1h was the largest for C3h. An opposite trend is observed for correlations in the streamwise direction, with C3h configurations having a significant correlation (greater than 0.2) for most of the canyon width (3\( h \)) and the C1h configurations having significant correlation lengths of approximately 0.5\( h \). The correlation could decay more rapidly for C1h than C3h because of a larger circulation region expected in a canyon with a larger \( AR \). It is also quite possible that the shear layer has an impact on the correlation decay. Blackman et al. (2015) computed the shear layer boundaries from vertical PIV data for the same configurations present in this work. The shear layer boundary was computed using the TKE production gradients in the shear layer to define a boundary with a threshold value (Blackman et al., 2015). They found that C3h had thicker shear layers than C1h. A thicker and larger shear layer would oscillate at a lower frequency, resulting in the flow in the canyon also having a lower frequency, which would be associated with a stronger correlation at near roof-level of the C3h canyon. In contrast, C1h was found to have a smaller shear layer, Blackman et al. (2015). The faster moving and thinner shear layer would cause the correlation at near-roof level to decay more rapidly. In the present work, the streamwise fluctuating velocity \( (R_{uu,x}) \) correlation at near-roof level was symmetrical for C1h but asymmetrical for C3h (see Figs. 18 and 19). This, again, can be explained by the shear layer boundaries computed by Blackman et al. (2015). They found the shear layer boundaries to be less
symmetrical (the symmetry of the shear layer can be defined by how constant the thickness is with respect to the streamwise position) in the streamwise direction for C3h than C1h. For C3h the shear layer boundary was much thicker at the downstream wall than near the upstream wall (approximately four times larger), this difference being significantly smaller for C1h (approximately two times larger). Hence, there appears to be a relationship between streamwise correlation symmetry at roof level and the geometry of the shear layer. Finally, it was stated above that the effect of roughness is much more profound on the near roof-level spanwise correlations for C1h than C3h canyons. This trend is, again, present in the shear layer boundaries computed by Blackman et al. (2015), with the C1h configurations varying more with roughness. Correlation decay in the streamwise direction was found to be related to shear layer boundaries in that those configurations with the thickest shear layer had the strongest correlations at roof level. Kang et al. (2008) conducted two-point correlations in the streamwise direction of the vertical turbulent velocities associated with simple aerodynamic cavities ($AR = 1$ and 2), which included no upstream roughness. The correlations went to zero much more rapidly than in the present case (approximately after $0.5h$). The stronger $R_{ww,x}$ correlations in the present work could be due to the larger scale structures and higher levels of turbulence generated by the upstream roughness. However, in both cases the $R_{ww,x}$ correlation goes below zero, which could be due to organized vortex shedding being present in both types of cavity flows.

The two-point correlations of spanwise ($R_{w}$) and vertical ($R_{ww}$) fluctuating velocities are also presented in Figs. 18 and 19 (refer to Fig. 20 for a complete summary of the correlation strengths for all configurations). The criteria proposed by Raupach et al. (1996) for significant a correlation can be also used for $R_{vv}$ and $R_{ww}$. The $R_{vv,y}$ was found to have a significant correlation length of approximately $1h$ for the C1hRcu and C1R1h configurations, with the C1hRcu remaining more correlated beyond the 0.2 threshold. The same pattern can be observed in the C3h configurations, with the skimming flow case having weaker $R_{vv,y}$ than in the 3D case. The wake interference flow cases (R3h) were found to have a much stronger $R_{vv,y}$, for both canyon configurations. The results from the $R_{ww,y}$ correlations suggest that roughness cases of R3h are the strongest, with the C3h canyon being significantly larger than the C1h. Ashcroft and Zhang (2005) reported
that the alternating pattern of positive to negative correlation for the vertical turbulent velocity represents an ordered collection of coherent structures. Little et al. (2007) also suggest that the alternating pattern represents the formation of large scale vertical structures. Negative values of $R_{ww,x}$ could be an indication of organized vortex shedding consistent with the organization within a mixing layer. In the C1h configurations, negative values of $R_{ww,x}$ are only observed for R1h (skimming flow), which could be related to the stronger flapping of the shear layer in the Rcu and R3h configurations. However, in both cases the $R_{ww,x}$ correlation goes below zero, which could be due to organized vortex shedding being present in both types of cavity flows. In their study of the flow over an open cavity, Kang et al. (2008) and Kang and Sung (2009) have, indeed, shown that large-scale swirling structures developing in the shear-layer at roof level leave their footprint in the two-point correlation of the vertical velocity component along the longitudinal direction in the form of negative values. Due to the size of the structures and the flapping motion animating the shear-layer, no more than one oscillation is usually visible in the correlation. This is especially true in the case of street canyon flows in which the high level of turbulence of the oncoming flow strongly increases the intermittent character of these swirling structures shed from the upstream obstacle (Perret and Savory, 2013). It must be noted that this strong intermittency has, so far, prevented the detection of any well-marked frequency in the flow that could be associated with the typical vortex shedding phenomenon downstream of a bluff-body. The $R_{vv,x}$ correlation was found to be stronger for the C1h cases than the C3h cases. A common trend observed was that the wake interference roughness cases (R3h) produced the strongest correlations (the Reynolds shear stress profiles in Fig. 14, also had the highest magnitudes for the R3h cases). It can be concluded the Reynolds shear stress is dependent on the strength of the streamwise and spanwise correlations for all three normal turbulent velocity components. Volino et al. (2009) suggest that the reason why the vertical fluctuating velocity correlations are less than the streamwise fluctuating velocity correlations, is due to the streamwise correlation being related to the convection velocity of hairpin packets in the boundary layer, a trend observed at roof-level in the present work.
Figure 18: Two-point correlations for C1h along the spanwise (y) and streamwise (x) centre lines a) $R_{uu,y}$; b) $R_{uu,x}$; c) $R_{vv,y}$; d) $R_{vv,x}$; e) $R_{ww,y}$; f) $R_{ww,x}$. 
Figure 19: Two-point correlations for C3h along the spanwise (y) and streamwise (x) centre lines a) $R_{uu,y}$; b) $R_{uu,x}$; c) $R_{vv,y}$; d) $R_{vv,x}$; e) $R_{ww,y}$; f) $R_{ww,x}$
2.3.4 Integral length scale

The turbulence integral length scale can be defined as the size of the average-energy containing eddy. The turbulence integral length scales were calculated using Eq. 3 for the spanwise direction velocity fluctuations and Eq. 4 for the streamwise direction velocity fluctuations. The reference points used to compute $R_{uu}$ used in Eq. 3 and Eq. 4 were $x_{ref} = -0.5h$, $y_{ref} = 0h$ for the streamwise $L_{uu}$ and $x_{ref} = 0h$, $y_{ref} = -3h$ for the spanwise $L_{uu}$. The integral length scale was computed by integrating until the first zero crossing of a two-point spatial correlation.
The integral length scales for the streamwise fluctuating velocity ($u'$), the spanwise fluctuating velocity ($v'$) and the vertical fluctuating velocity ($w'$) in the $x$ and $y$ directions are presented in Fig. 21. It may be seen that roughness and $AR$ have a significant effect on the spanwise integral length scale. $L_{uu,y}$ for C1hRcu was found to be almost 50% smaller than that for C1hR1h and C1hR3h. This suggests that whether the flow is 2D or 3D rather than the $\lambda_p$ influences the magnitude of $L_{uu,y}$. Blackman et al. (2015) found that the streamwise integral length scale was larger for the 2D case than the 3D case for the same $\lambda_p$. Volino et al. (2009) also observed that integral length scales were significantly smaller for 3D than for 2D cases. The results of Takimoto et al. (2013) contradict this as they showed larger $L_{uu}$ in the 3D configuration. However, as suggested by Blackman et al. (2015) this could be due to the simulation method employed, as no spires were used in the experiment, resulting in a thinner boundary layer. Blackman et al. (2015) found that, at roof-level ($z/h = 1$), the streamwise $L_{uu}$ for Rcu was approximately $4h$ but it is lower in the present work because the measurements were taken at $z/h = 0.9$. The present results show that that $L_{uu,y}$ is smaller for 3D than 2D flows, which was also found in previous work (Blackman et al., 2015 and Volino et al., 2009) for the streamwise direction. The integral length scales for vertical velocity fluctuations ($L_{ww}$) were found to be approximately three to four times smaller than $L_{uu}$. 

$$L_{uu,y} = \int R_{uu}(y)dy$$

(3)

$$L_{uu,x} = \int R_{uu}(x)dx$$

(4)
Figure 21: The effect of roughness on the integral length scale scaled with the canyon height. a) $L_{uu,y}$; b) $L_{vv,y}$; c) $L_{ww,y}$; d) $L_{uu,x}$; e) $L_{vv,x}$; f) $L_{ww,x}$.

The ratios between each of the spanwise and streamwise integral length scales are presented in Fig. 22, which shows that the ratios of the streamwise scales are significantly larger for the C1h case than the C3h cases. The ratio was found to be up four times larger for the R1h case. This is due to significantly larger spanwise $L_{uu}$ and, from the present results, it appears to be the dominating integral length scale in the C1h case. The ratio of the vertical integral length scales was found to be larger in the C3h cases, which could be due to larger turbulent structures at near roof-level in the C3h than the C1h configurations.
2.4 Summary

Horizontal measurements were conducted at near roof-level in a street canyon using particle image velocimetry in a wind tunnel, for six configurations, consisting of three upstream roughness configurations and two canyon aspect ratios.

a) The roughness plan area density ($\lambda_p$) was found to have a significant effect on mean statistics, correlations and integral length scales near roof-level. The present results agree with previous published results by Blackman et al. (2015), where measurements were conducted in a vertical plane over the same configurations as in the present work. It was found that the mean streamwise velocity was highest for the skimming flow regime case (R1h), being larger than both the wake interference (R3h) and 3D (Rcu) cases. However, for the same $\lambda_p$ the 3D configurations yielded smaller streamwise velocities than the 2D configurations. The mean vertical velocity was found to be lower in the C1h canyon than the C3h configurations, suggesting a lower level of vertical ventilation for smaller canyons at roof level. The trend of a higher AR canyon having a larger shear stress was found in the present work, as noted previously by Salizzoni et al. (2011), Michioka and Sato (2012) and Blackman et al. (2015).

b) It was observed that the two-point correlations were symmetrical for all quantities in the spanwise direction. Stronger correlations were found for the 2D roughness
arrays than in the 3D arrays and the planform packing density ($\lambda_p$) was found to have no effect on spanwise correlations. It was found that the correlation decay in the streamwise direction was related to shear layer boundaries such that the configurations with the thickest shear layer had the strongest correlation.

c) The integral length scales ($L_{uu}$) were found to be smaller for 3D than 2D flows in the spanwise direction. The integral length scales for vertical velocity fluctuations ($L_{ww}$) were found to be approximately three to four times smaller than $L_{uu}$. The ratio of the vertical integral length scales was found to be larger in the C3h cases, which could be due to larger turbulent structures at near roof-level in the C3h than the C1h configurations. Negative values of $R_{ww,x}$ could indicate organized vortex shedding. In the C1h configurations, negative values of $R_{ww,x}$ are only observed for R1h, this could be related to the stronger flapping of the shear layer than in the R3h and Rcu configurations. The circular radius of the two-point correlations suggests that the small-scales in the flow are rather isotropic and that their size depends on the upstream roughness configuration. Stronger spanwise correlations present in the R3h configurations suggests that wake-interference could be linked to larger spanwise flushing events in the street canyon. Elongated correlation structures in the streamwise direction for C3h configurations were found, while the structure of the correlation was elongated in the spanwise direction for the C1h configurations. Large scale spanwise organization of the flow suggested by Perret et al. (2016) was also confirmed here by the strength of the correlations in the spanwise direction, notably for the C1h configurations.

2.5 Conclusion

The present results provide useful information on the behaviour of the flow within a street canyon, used here as a simpler model to investigate the characteristics of the flow existing in one or several neighbouring streets within an urban area by removing the complexity induced by the presence of intersections. It can be concluded that there is a spanwise variation in the turbulence at roof-level which is dependent on characteristics of
the upstream flow and canyon geometry. Understanding the flow in the spanwise direction allows us to gain insight on the statistical spatial structure of the mechanism driving vertical momentum transport between the street canyon and the overlying boundary layer. Even if not definitive, because it is based on only six flow configurations, the present results clearly show the impact of both the canyon and upstream roughness configuration on the structure of the flow at roof level, the former being not the sole factor influencing the dynamics of the momentum exchange in this region.

2.6 References


Savory E, Perret, L, Rivet C (2013) Modelling considerations for examining the mean and unsteady flow in a simple urban-type street canyon. Meteorol Atmos Phys 121: 1–16


Chapter 3

Roof-level large- and small-scale sweeps and ejections

In the present chapter, the large and small-scale turbulent motions at roof-level of the street canyon are examined. Quadrant analysis is conducted to investigate spanwise sweep and ejection events. A spanwise spatial filter is used to investigate the large-scale motions in the flow. Triple decomposition is used to separate the large- and small-scales of turbulence in the flow. The present analysis was conducted on a range of experimental configurations. In total six configurations were studied: Three upstream roughness arrays and two canyon width ($W$) to height ($h$) aspect ratios ($AR = W/h = 1$ and $3$). The upstream roughness arrays consisted of 3D cubes (plan area density, $\lambda_p = 25\%$), a skimming flow regime ($1h$ spaced 2D bars, $\lambda_p = 50\%$) and a wake-interference flow regime ($3h$ spaced 2D bars, $\lambda_p = 25\%$). It was found that roughness has a significant effect on the size of the quadrant events in the street canyon, with the wake-interference flow regimes producing significantly larger sweep and ejection events than the skimming flow regimes. Wake-interference flow regimes were found to have a significantly greater temporal correlation than in the skimming flow regimes. It was found that there is an interaction between large- and small-scales at roof-level of the street canyon. Finally,
ejection events were found to be coupled with low-momentum regions and sweep events with high-momentum regions.

3.1 Introduction

Townsend (1976) proposed a hypothesis where the turbulence in a boundary layer close to the wall could be divided into “active” and “inactive” motions, where the active motions are responsible for vertical momentum transport and inactive motions are not. Active turbulence is a result of wind shear which scales on local parameters of the flow, while inactive turbulence is a product of processes distant from the wall and scales on outer-layer parameters, Bradshaw (1967) and Townsend (1976). In turbulent boundary layer flows, there are a variety of different types of coherent motions present, such as ejections of low-speed fluid outward away from the wall and sweeps of high speed fluid inward towards the wall (Robinson, 1991).

The presence of spanwise coherent structures in turbulent boundary layer flows over smooth surfaces has been well documented (Adrian, 2007, Hutchins and Marusic, 2007, Adrian and Tomkins, 2003, Robinson, 1991). Tomkins and Adrian (2003) investigated the spanwise structure and growth mechanisms in a turbulent boundary layer flow, showing that mean values of several spanwise length-scales increase linearly with the distance from the wall, suggesting self-similar growth of spanwise structures with height. There is less known about the structures present in urban roughness arrays, especially street canyon type flows. Through direct numerical simulation (DNS) Coceal et al. (2007) found that the development of hairpin vortices in a cubical roughness array via the relationship of low-momentum regions (LMRs) and regions of sweep (Q4) and ejection (Q2) events. It was observed that a shear layer forms within the roughness sub-layer (RSL) which contains small-scale structures partially produced by the recirculation within the street canyon. Large Eddy Simulations (LES) conducted by Cui et al. (2004) showed that flow at roof-level in the street canyon ($AR = 1$) is highly intermittent and filled with multi-scale turbulent events. Michioka et al. (2010), Michioka and Sato (2012) and Michioka et al. (2014) studied coherent structures generated near roof-level of street canyons. Michioka et al. (2010) and Michioka et al. (2014) found that coherent low-
momentum structures were directly linked to the ejection of fluid. Michioka and Sato (2012) and Michioka et al. (2014) showed that the size of the coherent structure was proportional to the amount of pollutant removed in the canyon. Flushing motions (large-scale upward motions) observed by Takimoto et al. (2011) were found to correlate with LMRs passing over the roughness canopy (single-vertical plane PIV measurements). They concluded that obtaining 3D information on the flushing motions present in street canyons would be indispensable. Chapter 2 showed that upstream roughness could have an influence on the spanwise size of the flushing events, from observing spanwise variation of integral length-scales in different roughness arrays. Inagaki and Kanda (2010) conducted a field experiment where they examined the coherent structures over a roughness array consisting of 1.5 m cubes. A spanwise spatial filter was used to decompose the velocity fluctuations into small- and large-scale contributions. In the active turbulence, they found large low-momentum elongated structures in the streamwise direction, which were said to account for a major part of the local Reynolds stress. These structures are expected to have an influence on the ventilation mechanism in the street canyon, as shown by Takimoto et al. (2011). The authors stated that the ventilation process is controlled not just by the neighbouring buildings but also by the larger scale motions developing above and upstream of the street canyon. The relationships between the complex structures found at roof-level in a street canyon flow and how they interact with intermittent events such as sweeps (Q4) and ejections (Q2), which are responsible for momentum exchange between the roughness sub-layer and inertial layer, need to be further investigated (Perret and Savory, 2013). Christen et al. (2007) demonstrated that quadrant analysis can be used to show that turbulent momentum transport and heat fluxes dominate large portions inside and above the street canyon, especially at roof-level where they were found to be mainly sweep events. It was found that at roof-level the exchange was more efficient (higher values of Reynolds shear stresses) and less intermittent than in other parts of the canyon. Kellnerova et al. (2013) conducted a quadrant analysis on various street canyon flow configurations (pitched and flat-roof street canyons). They found that sweep and ejection events occurred in the street canyon in an alternating fashion, when strong sweep events occurred there were less ejection events present and vice-versa. It was found that the sweep and ejection events
contained 80-90% of the total turbulent kinetic energy (TKE) in the street, making them the most important features in the flow at that instant. It was concluded that sweep and ejection events are the most important fractions of the momentum flux. They found the pitched-roof case yielded higher shear stresses and that the peak momentum flux at roof level was double that of a flat-roof street canyon, but a systematic investigation on the effect of the upstream roughness was not considered.

Perret and Ruiz (2013) studied coherent motions in vegetation canopies using Stereoscopic Particle Image Velocimetry (SPIV). Conditionally-averaged velocity fields based on the occurrence of ejections and sweeps revealed that there is a spanwise coherent motion which moves from high-speed to low speed-regions. The energy present in coherent motions in flows over vegetation canopies has been found to affect the time-averaged turbulence statistics, as well as contributing to the turbulence production and the momentum transfer (Shaw et al. 1995; Raupach et al., 1996; Finnigan, 2000; Watanabe, 2004; Finnigan et al., 2009). Finnigan et al. (2009) suggested that at the top of the canopy there exists a characteristic eddy which consists of an upstream head-down sweep generating hairpin vortex overlaid on a downstream head-up ejection generating hairpin. The sweep and ejection mechanisms were explained by pairs of superimposed head-up and head-down hairpin vortices that first generate a Q2 ejection and then a Q4 sweep as the hairpin pair convects downstream. They also noted that in the roughness sub-layer (RSL) the turbulence is more coherent and effective in transporting momentum and in most cases, its behaviour resembles a mixing layer more than a boundary layer. The RSL can be defined as being the distance from the surface to $2h-5h$, where $h$ is the height of the roughness elements. The RSL is the region where the flow is influenced by individual roughness elements, which is reflected in the spatial inhomogeneity of the mean flow (Bottema, 1996, Castro and Chang, 2002). The mixing-layer analogy (active turbulence and coherent motions near the top of the roughness are organized in a plane mixing-layer) was proposed by Raupach et al. (1996), but the model was not able to explain the transition from sweep dominance to ejection dominance as the distance from the wall or roughness increased. Finnigan and Shaw (2000) showed that sweeps dominated momentum fluxes at $0.2 > z/h > 1.2$ rather than ejections. Yue et al. (2007)
conducted quadrant analysis on a vegetation canopy and found that near the canopy top, ejections were the most frequently occurring events but sweeps contributed most to the momentum flux. Finnigan et al. (2009) found that the sweep contribution to the total shear stress was dominant within the canopy up to \( z / h = 1.3 \) and that the ejection contribution to the shear stress is increasingly more important above that level.

A significant experimental effort has been made to conduct systematic wind tunnel studies on street canyon flows (Salizzoni et al. 2011; Takimoto et al. 2013; Savory et al. 2013; Blackman et al. 2015). In these studies, the upstream roughness was defined by having 2D or 3D roughness elements and by the plan area packing density (the ratio of the plan area of the roughness obstacles to the total plan area, denoted as \( \lambda_p \)). The canyon aspect ratio \((AR)\) was defined as being the ratio between streamwise width \((W)\) and canyon height \((h)\). The results presented in Ch. 2 (horizontal SPIV measurements at roof-level of the street canyon) showed that upstream roughness had a significant effect on the mean turbulent statistics (mean velocities, standard deviations and Reynolds shear stresses), two-point correlations and integral lengths scales. Skimming flow (2D bars with spacing of \(1h\)) and 3D (staggered cube array with heights of \(1h\)) upstream roughness configurations were found to have significantly weaker correlations in the spanwise direction than the wake-interference flow (2D bars with spacing of \(3h\)) upstream roughness configurations. A similar trend was observed in the integral length-scales. Two-point correlations revealed that multiple scales of motion are present at roof-level in a street canyon type flow.

There is a variety of different scales of motion in various flows ranging from smooth wall turbulent boundary layers to street canyon flows. There exists a non-linear interaction between large- and small-scales between the roughness sub-layer and inertial sub-layer. The non-linear interaction between large- and small-scales is linked to a mechanism of amplitude modulation (Hutchins and Marusic., 2007). Squire et al. (2016) observed this mechanism over a sand-roughened wall. It has been shown by Mathis et al. (2011) that

\[
\overline{u_L^2 u_s} \quad (u_s' \text{ denotes the streamwise fluctuating velocity, the overbar denotes time-averaging})
\]

term represents the influence of the large-scale \((u_L')\) momentum region on the small-scales \((u_s')\) through an amplitude modulation mechanism. Basley et al. (2018)
found spatial modulation of the small-scale turbulence nearby the footprint of large-scale motions, in the RSL over a $\lambda_p = 25\%$ cubical array. They found that the turbulence is enhanced near the front of high momentum regions and dampened at the from of low momentum regions. Blackman and Perret (2016) investigated the mechanism of amplitude modulation of the small-scales by the large-scales over a $\lambda_p = 25\%$ cubical array and found that a non-linear interaction was present. Blackman et al. (2018) investigated the modulation of small-scale structures by large-scale structures in a street canyon flow. They used a multi-time delay stochastic estimation to decompose the flow into large- and small-scales. They found an influence of upstream roughness geometry and $\lambda_p$ on the non-linear interactions between the small-scales created by the roughness and the large-momentum regions. The wake-interference flow regime was found to have more scale-modulation than the skimming flow regime.

Hutchins and Marusic (2007) described “superstructures” as being a regime of long meandering positive and negative velocity fluctuations, which are found to exist in the log and lower wake regions of the turbulent boundary layer. Near-wall, small-scale turbulence was found to be affected by the meandering large scale structures higher in the boundary layer, Hutchins and Marusic (2007). The effect that the roughness has on the non-linear interactions between scales should be further investigated. The systematic street canyon investigation by Blackman et al. (2018) and the study of flow over a $\lambda_p = 25\%$ cubical array by Blackman and Perret (2016) provide significant contributions to effect of roughness on scale-modulation in street canyon flows. However, the spanwise organisation of the interactions of small-scales and large-momentum regions still needs to be investigated to better understand the 3D behaviour of this mechanism.

To the knowledge of the present author, a systematic study of the effects of canyon aspect ratio and upstream roughness on the spanwise behaviour of sweep/ejection events and large/small-scale interactions has not been conducted. Spanwise horizontal measurements provide useful information because the flapping shear layer present in this region of the street canyon controls the sweep and ejection events, which regulate ventilation at the canyon top. The present work focuses on the spanwise variation of the quadrant events (Q1, Q2, Q3 and Q4), the spatio-temporal correlation of the flow and the interactions of
large- and small-scale motions at roof-level in a street canyon flow. The large-scale component of the flow is obtained through spanwise spatial filtering. The questions to be addressed in the present study are:

a) What effects do canyon aspect ratio (AR) and upstream flow regime have on the small- and large-scale spatio-temporal correlations at roof-level in a street canyon flow.

b) What effects do canyon aspect ratio (AR) and upstream flow regime have on the quadrant events at roof-level of the canyon?

c) How does the large- and small-scale turbulence at roof-level interact with the flow in the boundary layer above?

The next section describes the experimental facility, the roughness and canyon configurations examined and the SPIV setup. This is followed by a discussion of the results after which some conclusions are drawn.

3.2 Methods

The following section describes the experimental setup used in the present work and the methodology used study the large- and small-scale turbulent motions at roof-level in the street canyon. Section 3.2.2 contains a description of the quadrant analysis used to identify the sweep, ejection, inward and outward interaction events present in the measurement region. Section 3.2.3 contains a definition of the spatial filter which is used to separate the large- and small-scale motions in the flow. The method of computing the two-point spatio-temporal correlation is presented in Section 3.2.4.


3.2.1 Experimental setup

The experiments were conducted at the LHEEA atmospheric boundary layer wind tunnel in Nantes, France. The wind tunnel has a working section of $24 \times 2 \times 2$ m (length $\times$ width $\times$ height) and a range of roughness elements (vertical tapered spires and staggered cube arrays) were used to initiate boundary layer development. After the initial development region (comprised of 13 m fetch of staggered cubes) three different roughness configurations were used. They consisted of a 5.5 m fetch of staggered cubes, $1h$ and $3h$ spaced bars (all of having a height of 50-mm). The street canyon measurements were taken after this region. The street canyon was constructed using two square cross section rectangular bars (height of 50-mm and a lateral length, $L$ of 1500-mm). In earlier experiments, Blackman et al. (2015) demonstrated that the length of the initial development region was sufficiently long that the change from the staggered cubes (initial development region) to the 2D bars was long enough so that the internal boundary layer reached equilibrium by the measurement region. Savory et al. (2013) showed that the centre-line mean statistics were independent of canyon length when $L/h \geq 9$ (whereas in the present work $L/h = 30$ is used). The six flow conditions used in Blackman et al. (2015) were also used here. Namely, two canyon ARs with the three different upstream roughness configurations were used. Street canyons of $AR = 1$ and 3 are denoted as C1h and C3h, respectively. The upstream roughness conditions consisted of a staggered cubical array ($\lambda_p = 25\%$, denoted as Rc) or 2D square cross section rectangular bars with a spacing of $1h$ or $3h$ ($\lambda_p = 25\%$ and $\lambda_p = 50\%$, denoted as R1h and R3h, respectively). For example, the configuration consisting of a street canyon with of $AR = 1$ and a 3D staggered cube upstream roughness is denoted as C1hRcu. Stereoscopic PIV was used to measure the flow. Measurements were conducted in a horizontal plane located at a height of $z = 0.90 \pm 0.05h$. A schematic of the experimental setup is presented in Fig. 23.
Figure 23: Experimental setup, where ● denotes the reference point located at ($x = 0$, $y = 0$, $z = 0.9h$).

The temporal sampling frequency was 7 Hz and a final spatial resolution of 1.6 mm (0.032$h$) was obtained in both $x$ and $y$ directions. A pitot-static tube located at $x = 15$ m, $y = 0$ m, $z = 1.5$ m was used to measure the reference dynamic pressure, giving a freestream velocity of $U_e = 5.9$ m s$^{-1}$. In the present work, the following conventions were used: The streamwise ($U$), spanwise ($V$) and vertical ($W$) velocities were defined as being in the $x$, $y$ and $z$ directions respectively. Fluctuating velocities are defined as the fluctuation from the mean. Definitions of the mean turbulent statistics are summarized in Table 3 and a summary of the experimental details can be found in Table 4, whilst a summary of the boundary layer characteristics and scaling parameters can be found in Table 5.
Table 3: Formulations of mean turbulent statistics. $U(t)$ denotes the instantaneous $u$-component velocity and $u'(t)$ the velocity fluctuation from the mean ($\overline{U}$). Time averaging is denoted by an overbar. Spatial averaging is denoted by $<k>$.  

<table>
<thead>
<tr>
<th>Mean Velocity</th>
<th>$\overline{U} = U(t) - u'(t)$.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard Deviation</td>
<td>$\sigma_u = \left( \frac{(U(t) - \overline{U})^2}{\overline{U}} \right)^{1/2}$.</td>
</tr>
<tr>
<td>Reynolds Shear Stress.</td>
<td>$\overline{u'w'} = (U(t) - \overline{U})(W(t) - \overline{W})$.</td>
</tr>
</tbody>
</table>

Table 4: A Summary of the experimental parameters.

<table>
<thead>
<tr>
<th>SPIV sampling freq.</th>
<th>7 Hz</th>
<th>Statistical error of $\overline{U} / \overline{U}_{z=0.9h}$</th>
<th>0.86%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pulse interval</td>
<td>500 $\mu$s</td>
<td>Statistical error of $\sigma_u / \overline{U}_{z=0.9h}$</td>
<td>1.41%</td>
</tr>
<tr>
<td>Freestream velocity $(U_e)$</td>
<td>5.9 $\text{ms}^{-1}$</td>
<td>Mean diam. of seeding particles</td>
<td>1 $\mu$m</td>
</tr>
<tr>
<td>Reynolds Number $(U_e h / \nu)$</td>
<td>$1.9 \times 10^4$</td>
<td>Laser energy/pulse</td>
<td>$2 \times 200 \text{mJ}$</td>
</tr>
<tr>
<td>Spatial resolution</td>
<td>0.032$h$</td>
<td>Vector fields / config.</td>
<td>10000</td>
</tr>
</tbody>
</table>
Table 5: Oncoming boundary layer characteristics where $u_*$ denotes friction velocity, $d$ denotes the displacement height and $z_o$ denotes the roughness length. (Blackman et al., 2015). The kinematic viscosity is denoted by $\nu$.

<table>
<thead>
<tr>
<th>Roughness</th>
<th>$\lambda_p$ (%)</th>
<th>$u_*/U_e$</th>
<th>$d/h$</th>
<th>$z_o/h$</th>
<th>$h/u_*$</th>
<th>$Re$</th>
<th>$Re_{U_e h / \nu}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rcu</td>
<td>25</td>
<td>0.066</td>
<td>0.892</td>
<td>0.061</td>
<td>4.472</td>
<td>1.2×10^4</td>
<td>1.9×10^4</td>
</tr>
<tr>
<td>R1h</td>
<td>50</td>
<td>0.047</td>
<td>0.980</td>
<td>0.008</td>
<td>6.272</td>
<td>1.2×10^4</td>
<td>1.9×10^4</td>
</tr>
<tr>
<td>R3h</td>
<td>25</td>
<td>0.072</td>
<td>0.522</td>
<td>0.143</td>
<td>4.094</td>
<td>1.6×10^4</td>
<td>1.9×10^4</td>
</tr>
</tbody>
</table>

3.2.2 Quadrant analysis

Quadrant analysis is a method where the turbulent momentum flux, $u'w'$, is separated into four quadrants. In the present work, the following scheme is used:
- $u' > 0, w' > 0$: Quadrant 1 (Q1) – outward interaction,
- $u' < 0, w' > 0$: Quadrant 2 (Q2) – ejection,
- $u' < 0, w' < 0$: Quadrant 3 (Q3) – inward interaction,
- $u' > 0, w' < 0$: Quadrant 4 (Q4) – sweep,

In the present work, the data-set is divided into four quadrants and each quadrant data-set is composed of a series of binary (1s and 0s) maps which identify where a given quadrant event was detected. The objective of this analysis is to compute two-point correlations on the binary maps and determine the average size of the quadrant events in each configuration. A schematic of the analysis procedure can be found in Fig 24.
Figure 24: Schematic of quadrant analysis conditions applied to the data to generate four binary data-sets. Binary data-sets were taken from a random snapshot for the C1hRcu configurations.

A two-point spatial correlation of the four quadrant events (binary data-sets of: Q1, Q2, Q3 and Q4) was conducted using the middle of the street canyon ($x_{ref} = 0h$, $y_{ref} = 0h$, $z_{ref} = 0.9h$) as the reference point. The two-point correlation coefficient of the binary sets of the four quadrant events was computed using Eq. 5.

$$R_{Qi}(x_{ref}, y_{ref}, x, y) = \frac{Q_i(x_{ref}, y_{ref})Q_i(x, y)}{\sqrt{Q_i^2(x_{ref}, y_{ref})Q_i^2(x, y)}}$$  (5)

The two-point correlation of the binary quadrant data sets can be used to estimate the average size of each quadrant event. The computed correlation fields were subject to a threshold of 0.4, where any correlation coefficient bellow this value was ignored ($R_{Qi} < 0.4 = 0$). The area in which the correlation is greater than 0.4 approximates the size and structure of the quadrant event, through the estimation of the integral length-scale. The 0.4 value was selected as it roughly corresponds to an integral scale spatial separation (Wang and George, 2011, Kaimal and Finnigan, 1994).
3.2.3 Spanwise Filter, $\Delta$

A spanwise spatial filter is used to remove the high-frequency velocity signal from the SPIV data and retain the low-frequency signal. Inagaki and Kanda (2010) stress the importance and difficulty of selecting a reasonable filter size. The filter cut-off should be a length scale that separates the active and inactive fluctuations. The size of the active turbulence can be related to the size of the roughness elements and the scale of the inactive turbulence is related to boundary layer height (Inagaki and Kanda., 2010). The ratio of the filtered turbulent intensities to the unfiltered turbulent intensities can be used to determine an appropriate filter size. Perret and Ruiz (2013) used this method to determine a filter size of $9.8h$ from data obtained at a height of $z/h = 1.5$. Inagaki and Kanda (2010) found an appropriate spanwise filter size to be $20h$ from data obtained at a height of $z/h = 2$. The present filtering analysis was conducted on a horizontal plane ($x$-$y$) at roof-level of the street canyon. A moving average filter with a width of $\Delta$ was used on the three velocity components to filter out the high frequency signal and conserve the low-frequency signal. The low-frequency filtered velocity is presented in Eq. 6, where $u_t$ is the original (unfiltered) velocity signal, $t$ denotes time and $\hat{y}$ is the position of the filter. The width of the spanwise filter is measured from $y = 0$ to $y = \Delta$.

$$\bar{u}_t(x,y,t) = \frac{1}{\Delta} \int_{\hat{y} = y}^{\hat{y} = y + \Delta} u_t(x,\hat{y},t) d\hat{y}$$

In the present work, the spanwise filter length was determined to be $4.5h$. The evolution of the ratio between the spatially (denoted by $<$ >) and temporally (denoted by $\bar{\cdot}$) averaged turbulent intensities for the filtered and unfiltered data are presented in Fig. 25. Referring to Fig. 25 it can be observed that as $\Delta$ is increased the ratios between filtered and unfiltered values of turbulent intensities decreases, as the amount of fluctuation in the signal decreases. When $\Delta \approx 4.5h$, the filtered $< u'w' >$ and $< w'w' >$ account for about 35% of their unfiltered values and 45% for $< u'u' >$ and $< v'v' >$. The present filter width allows for minimum values of $< u'u' >$, $< v'v' >$, $< w'w' >$, and $< u'w' >$.
relative to their unfiltered counterparts. The size of the filter depends strongly on the Reynolds number, experimental setup, the measurement method and location. This can be observed through the differences in filter sizes between Inagaki and Kanda (2010), Perret and Ruiz (2013) and the present work.

Figure 25: Evolution of the ratio of the turbulent intensities and stresses filtered in the spanwise direction (SF) to their unfiltered value for different filter sizes. Filter applies to all configurations. The C3hRcu configuration is shown.

The large-scale velocity fluctuation (obtained by computing the fluctuating velocity from the filtered data), \( u'_L \) can be used to compute the small-scale fluctuating velocity by subtracting it from the fluctuating velocity in the original signal. The fluctuating small-scale velocity is defined as: \( u'_S = u' - u'_L \). A triple decomposition can be used to decompose the streamwise velocity (\( U \)) into a large-scale velocity fluctuation (\( u'_L \)), a small-scale velocity fluctuation (\( u'_S \)) and a time averaged mean (\( \overline{U} \)), as given by Eq. 7.

\[
U = \overline{U} + u'_L + u'_S
\]  

The filtering operation is applied for the all six flow configurations and to all the three velocity components (\( U, V, \) and \( W \)) with the same filter size (\( \Delta/h = 4.5 \)).

Skewness is a third order statistic which can be used to understand the non-linear interactions in a turbulent flow. The decomposition of the skewness can quantify these
multi-scale non-linear interactions (Blackman and Perret, 2016). The skewness decomposition is presented in Eq. 8.

\[
\overline{u'^3} = \overline{u'_L^3} + 3\overline{u_L u'_S^2} + 3\overline{u'_L u_S^2} + \overline{u'_S^3}
\]  

(8)

The cross-terms \(\overline{u_L u'_S^2}\) and \(\overline{u'_L u_S^2}\) represent the influence of large-scales onto small-scales and small-scales onto large-scales, respectively (Mathis et al. 2011). Mathis et al. (2011) conducted the scale decomposition on a smooth boundary layer flow and found that small-scales accounted for approximately 90% of the skewness, the cross-term \(\overline{u_L u'_S^2}\) was found to be negligible and the \(\overline{u'_L u_S^2}\) term was non-negligible. Within a smooth wall boundary layer the non-linear interaction \(\overline{u_L u'_S^2}\) has been connected to the mechanism of amplitude modulation (Hutchins and Marusic, 2007).

### 3.2.4 Spatio-temporal correlations

Two-point space-time correlations of the velocity fluctuations provide a wealth of information about the statistical and geometrical structure of the eddies in turbulent flows. In the present work, a two-point spatio-temporal correlation analysis was conducted using the centre of the street canyon \((x_{ref} = 0h, y_{ref} = 0h)\) as the reference point. The formulation of the two-point space-time correlations is presented in Eq. 9, where the time-lag is denoted as \(\tau\) and the correlation coefficient as \(R_{uu}\).

\[
R_{uu}(x_{ref}, y_{ref}, x, y, t) = \frac{u'(x_{ref}, y_{ref})u'(x, y, t + \tau)}{\sqrt{u'^2(x_{ref}, y_{ref})} \sqrt{u'^2(x, y, t + \tau)}}
\]

(9)

### 3.3 Results and Discussion

In this section, the results are presented and discussed. Section 3.3.1 investigates the spatio-temporal organization of the different scales of motion in the flow by computing two-point space-time correlations on unfiltered and filtered data. Section 3.3.2 contains a
quadrant analysis which demonstrates the variation of the quadrant events (Q1, Q2, Q3 and Q4) with upstream roughness and canyon aspect ratio (AR). It should be stressed that SPIV was used to measure the flow field, with the vertical velocity component being the reconstructed one. Therefore, caution should be taken when interpreting results from analysis that rely on the vertical velocity component, such as quadrant analysis.

3.3.1 Spatio-temporal organization of the flow

Inagaki and Kanda (2010), Perret and Ruiz (2013) demonstrate that large-scale motions can be extracted by applying a spanwise filter to the data. The spatio-temporal organization of the large-scale motions is investigated by computing two-point space-time correlations on spanwise filtered data. 3D surface plots of the unfiltered and filtered spanwise spatio-temporal correlations for streamwise ($u'$), spanwise ($v'$) and vertical ($w'$) fluctuating velocities (with $x_{ref} = 0h$, $y_{ref} = 0h$ set as the reference point) can be found in Fig. 26 and Fig. 27, for cases C1hR1h and C3hR3h, respectively and normalized by a time-scale, $h / u^*$. The 3D surface plots for the other four configurations can be found in Appendix B. The time-scales used in the present work can be found in Table 3. Plots of the temporal correlations (with $x_{ref} = 0h$, $y_{ref} = 0h$ as the reference point) for the three components for both unfiltered and filtered results normalized by $h / u^*$ are presented in Fig. 28 and Fig. 29 for C1h and C3h configurations respectively. The spatial filter, upstream roughness and canyon AR all strongly influence the spatial-temporal correlations.

The upstream roughness significantly affects the unfiltered spanwise spatio-temporal correlations for both C1h and C3h canyons. Referring to Figs. 28 and 29, the wake-interference (R3h) configurations demonstrate significantly higher correlation than the skimming flow configurations (R1h). The spanwise filter has the smallest effect on the spatio-temporal correlations of the vertical velocity fluctuations ($R_{ww}$). The $R_{ww}$ temporal correlation is found to be virtually unaffected by the spanwise filter for both C1h and C3h canyons (Refer to Figs 28c and 29c). The spatio-temporal correlations of the streamwise ($R_{uu}$) and spanwise ($R_{vv}$) velocity fluctuations increased after the filter was applied,
suggesting large-scale motions are present. The large-scales obtained via spanwise filtering correspond to long-term temporal correlation. The large-scale streamwise fluctuating velocities were found to have the strongest temporal correlation. This suggests that the size of the streamwise large-scale structures is largest. The spanwise fluctuating velocities were found to have stronger long-term temporal correlations than the vertical velocity fluctuations. This is a result of larger-scale motions being present in the spanwise component. The R3h configurations had the strongest long-term temporal correlations and the R1h configurations the weakest. Referring to Fig 28a., a negative temporal correlation of the streamwise fluctuating component for the C1hR1h case exists. The alternating pattern of a negative correlation could indicate an organized collection of turbulent structures (Ashcroft and Zhang, 2005). Chapter 2 presented that an alternating pattern of negative to positive correlations for the two-point spatial correlation coefficient of the vertical fluctuating velocity ($R_{ww}$). The correlations suggest that this could be due to organized vortex shedding, due to the stronger flapping shear layer in the skimming flow regime. Perret and Ruiz (2013) found large spanwise motions over a vegetation canopy, and suggested that the spanwise component was involved in inactive superstructures that consisted of low or high speed regions which meandered in the horizontal plane. These structures were referred to as “very large spanwise motions” (VLSM), and were said to have a streamwise length scale of the order of several times the height of the boundary layer. In the present work, the significant increase of the spatio-temporal correlation for the spanwise component (with a strong long-term temporal correlation) suggests the presence of large-scale spanwise motions in the flow at roof-level, which could possibly be an imprint of the VLSMs and large-scale superstructures above (Hutchins and Marusic., 2007).

The significant spatial correlation is defined arbitrarily to be $R_{uu} > 0.2$ (Shaw et al., 1996;). The region of significant correlation in the filtered correlations are all much higher compared to their unfiltered counterparts. The upstream roughness and canyon $AR$ do not have a notable effect on the filtered spanwise two-point correlations. The six configurations investigated all had significant correlations spanning roughly the entire width of the canyon ($6h$). The roughness and canyon $AR$ have a strong effect on the variation of the spanwise two-point correlations and the wake-interference flow regimes
have correlations larger than the skimming flow regimes. Blackman et al. (2015) found that R3h upstream roughness configurations had higher values of shear stress and turbulent kinetic energy (TKE) than R1h configurations. Blackman et al. (2015) also found that the shear layer was thicker for R3h than R1h configurations and this trend appears in the present temporal correlations as well. The temporal correlations and the spanwise two-point correlations in the present work correspond to the shear layer boundary thickness computed by Blackman et al. (2015). For example, the strongest spatio-temporal correlations were exhibited by the R3h configurations, in Blackman et al. (2015) the shear layer boundary was found to be thickest for the R3h configurations as well. This suggests that two-point spanwise correlations and temporal correlations could relate to the thickness of the shear layer.
Figure 26: 3D surface plots of the spanwise space-time correlations for unfiltered and filtered data, a) $R_{uu}$ – unfiltered b) $R_{uu}$ – filtered c) $R_{vv}$ – unfiltered d) $R_{vv}$ – filtered e) $R_{ww}$ – unfiltered f) $R_{ww}$ – filtered. Configuration shown: C1hR1h.
Figure 27: 3D surface plots of the spanwise space-time correlations for unfiltered and filtered data, a) $R_{uu}$ – unfiltered b) $R_{uu}$ – filtered c) $R_{vv}$ – unfiltered d) $R_{vv}$ – filtered e) $R_{ww}$ – unfiltered f) $R_{ww}$ – filtered. Configuration shown: C1hR3h.
Figure 28: Temporal correlations of a) $R_{uu}$, b) $R_{vv}$ and c) $R_{ww}$ for C1h configurations. SF denotes spanwise filtering.
Hutchins and Marusic (2007) showed that the superstructures present in a turbulent boundary layer were responsible for modulating near-wall small-scale activity. Blackman and Perret (2016) investigated flow over a cubical roughness. They showed through spatio-temporal correlations, that large-scale momentum regions influence small-scale structures throughout the boundary layer. Blackman et al. (2018) investigated the effect
of roughness on the modulation of non-linear interactions between the small-scales generated by the roughness elements and the large-scales above. They found that increasing the packing density and changing the upstream roughness from 3D to 2D increased the non-linear interactions of the large-scales and small-scales between the roughness sub-layer. The spatio-temporal spanwise structure of the flow appears to be related to the amplification of the small-scale structures in the roughness sub-layer. Blackman et al. (2018) noted that there is a significant difference between skimming flow and wake-interference flow regimes and the present results confirm that this trend also exists in the spanwise direction. The stronger spatio-temporal correlations for R3h could be a result of the increase of scale modulation in the wake-interference regimes (R3h) found by Blackman et al. (2018). The \( u'_L u'_S \) is a cross-term representing the influence of the large (L) scales onto the small (S) scales, which is obtained from the scale decomposition of the skewness of the streamwise component (Perret and Blackman, 2016; Blackman et al., 2018) and, here, it is computed by obtaining the large and small-scale fluctuations from spanwise filtering (see Sec. 2.2.2). The streamwise profiles of \( u'_L u'_S \) for the C1h and C3h canyons are presented are in Fig. 30a and Fig. 30b, respectively. The streamwise (x), spanwise (y), and time-averaged values of the contribution of \( u'_L u'_S \) to the skewness for all configurations are presented in Fig. 30c. Blackman et al. (2018) found that the large to small-scale interactions are dependent on upstream roughness.
Figure 30: Time-averaged and spatially-averaged in the spanwise direction streamwise profiles of the $u_i' u_S' z^2$ term for a) C1h configurations b) C3h configurations c) Time-averaged and partially-averaged in the spanwise and streamwise directions of $u_i' u_S' z^2$ values for all the configurations. $< >_{x,y}$ denotes spatial averaging in the streamwise and spanwise directions and $< >_{y}$ denotes averaging in the spanwise direction.

Thicker shear layer boundaries (Blackman et al., 2015) and stronger spanwise and temporal correlations are found in the wake-interference flow regimes, which could be associated with a larger modulation of small-scales by larger-scales at roof-level in a street canyon flow. From temporal correlations, the R3h configurations had the largest spanwise motions and corresponded to the largest scale modulations in Blackman et al. (2018).
The discrepancies between the present results and the work of Blackman et al. (2018) are due to the different filtering methods used. Blackman et al. (2018) used the method of stochastic estimation (refer to Blackman and Perret, 2016; Mathis et al., 2011) to separate the large-scales and small-scales of turbulence, which consisted of using a low-pass filter (cut-off frequency = \( \delta \)) on a reference HWA (located at \( z / h = 4 \)) and cross-correlating the signal with a near-wall PIV signal. Blackman and Perret (2016) state that the filtering method removes all small-scale energy in the signal. The spanwise spatial filtering technique used in the present work did not remove all the small-scale energy in the signal, referring to Table 6, the contribution of the small-scales to the total shear stress was found to be up to 53.56%. Blackman and Perret (2016) also found discrepancies between the work of Perret and Rivet (2013) were identical flows were studied. They attributed the inconsistency to the use of different decomposition methods. The work of Perret and Rivet (2013) used POD to decompose the flow, the separated large-scale energy was thought to encompass some small-scale energy as well.

When Blackman and Perret (2016), Blackman et al. (2018) decomposed the streamwise skewness, they found that at roof-level the \( u_L^3 \) and \( u_L^2 u_s \) terms from the skewness decomposition were negligible and that \( u_s^3 \) followed by \( u_L u_s^2 \) contributed most to the skewness. Referring to the Fig. 31, the present results agree qualitatively to Blackman et al. (2018). The present results were only found to agree when enough small-scale energy was removed from the original signal. In C1hR3h and C3hR3h the results did not agree due to insufficient filtering of the small-scale energy in the original signal. Nevertheless, it can be concluded that the spanwise spatial filter used in the present work can reproduce the same trends in the non-linear scale-modulation, provided that a sufficient percentage of the small-scale energy from the original signal is filtered out.
Table 6: The contribution of large-scale ($u'w'_L$) and small-scale ($u'w'_S$) shear stress to the total shear stress ($u'w'$) for six configurations.

<table>
<thead>
<tr>
<th></th>
<th>C1hR3h</th>
<th>C1hRcu</th>
<th>C1hR1h</th>
<th>C3hR3h</th>
<th>C3hRcu</th>
<th>C3hR1h</th>
</tr>
</thead>
<tbody>
<tr>
<td>$100 * (u'w'_L/u'w')$</td>
<td>55.14%</td>
<td>66.81%</td>
<td>72.65%</td>
<td>46.44%</td>
<td>62.47%</td>
<td>71.34%</td>
</tr>
<tr>
<td>$100 * (u'w'_S/u'w')$</td>
<td>44.86%</td>
<td>33.19%</td>
<td>27.35%</td>
<td>53.56%</td>
<td>37.47%</td>
<td>28.66%</td>
</tr>
</tbody>
</table>

Figure 31: Streamwise profiles of the streamwise skewness, $u^3$ including $u^3_L$, $u_Lu^2_S$, $u^2_Lu_s$ and $u^3_s$. Where $<>_y$ denotes spatial averaging in the spanwise direction. All quantities are normalized by $\sigma_u^3$. 
The present results suggest that the large-scale spanwise motions detected by the temporal correlations could influence the large- to small-scale interactions. However, as suggested by Blackman et al. (2018), it is important to investigate additional upstream roughness arrays to fully understand the influence of roughness on large- and small-scale interactions. The following section builds on large- and small-scale structures in the flow by investigating if the size of large- and small-scale sweep and ejection events present in each configuration.

### 3.3.2 Quadrant analysis

Quadrant analysis of the entire measurement region was conducted using the criteria given in (Sec. 2.2.1), on the unfiltered data and on the small- and large-scales obtained from the spanwise filtering (Refer to Sec. 2.2.2). The mean velocity profiles of the quadrant events can be found in Appendix A. The number of occurrences of each event divided by the total number of occurred events is presented in Fig. 32. Shaw (1985) found that sweeps (Q4) marginally exceeded ejections (Q2) at $z / h = 1.6$ (wheat canopy) and Perret and Ruiz (2013) found that the number of Q4 events was larger than Q2 events at $z / h = 1.2$ (vegetation canopy). Referring to Fig. 32, the opposite trend is observed, the ejection (Q2) events are more frequent for both C1h and C3h configurations. The differences could be due to the measurement plane being positioned horizontally instead of vertically in the present work and located inside the roughness ($z / h = 0.9$). It can be observed that the C3h configurations have a significantly higher (roughly two times) number of sweep (Q4) and ejection (Q2) events than inward (Q3) and outward (Q1) interactions. Kanda et al. (2004) conducted a Large Eddy Simulation (LES) over different cubical arrays ($\lambda_p = 11\%, 25\%$ and $44\%$), they found that inside the canyon sweep and ejection events were equal in contribution to the Reynolds shear stress in all cases. Larger vertical fluctuating velocity spanwise integral length scales ($L_{ww,y}$) and higher levels of turbulent shear stress ($\overline{u'w'}$) are present in C3h than in C1h configurations. This could be related to the larger number of Q2 and Q4 events in the C3h canyon. Kanda et al. (2003) reported that sparse arrays ($\lambda_p = 11\%$) had more momentum transfer at roof-level of the
canyon than the dense arrays ($\lambda_p = 44\%$). The momentum transfer in the R1h ($\lambda_p = 50\%$) and R3h ($\lambda_p = 25\%$) configurations follows the same trend. Decreasing the $\lambda_p$ increases the mean regions of Q2 and Q4 events. Takimoto et al. (2011) observed vertical flushing motions inside a street canyon type flow and the higher number of ejections (Q2) present in both configurations here could also be in fact an indication of the presence of such flushing motions. Flushing motions consist of inward interactions (Q1) and ejections (Q2), the present work shows that ejections contribute significantly more to flushing motions than inward interrelations (Refer to Figs. 33 and 34). The boundaries of each quadrant event for the C1h configurations are presented in Fig 33. and the same plots for the C3h configurations can be found in Fig. 34. The large- and small-scale plots of the quadrant events can be found in Appendix A.

**Figure 32:** The number of events for each quadrant event, presented as a percentage of total events a) C1h and b) C3h. Computed by: $100 \times (Q_i / Q_{TOTAL})$, where $i$ is the quadrant event.
Figure 33: The correlations contours of quadrant events in the C1h canyon where a cut-off of 0.4 is used to approximate the average size of the event. a) C1hRcu b) C1hR1h c) C1hR3h.

The R3h upstream roughness configurations have the largest sweep (Q4) and ejection (Q2) events, followed by Rcu and R1h, independent of canyon size. Chapter 2 showed the same trend for spanwise and streamwise two-point correlations on the vertical fluctuating velocity component. The C1hR1h configuration stands out with the average size of the four quadrant events essentially being the same. The size of Q2 and Q4 events for C3hR1h is significantly smaller than for the other C3h configurations. Referring to Fig. 33 and Fig. 34 it can be observed that roughness significantly affects the Q4 and Q2 events and has a smaller impact on the Q3 and Q1 events. It can be concluded that the canyon AR influences the size of the quadrant events. The C1hR1h configuration, has sweep and ejection events (Q4 and Q2, respectively) that do not differ greatly in average size from the inward and outward interactions (Q3 and Q1, respectively). However, for the C3hR1h configuration the ejection events are larger than the sweep events and the inward and outward interactions were found to be much smaller than the sweeps and ejections. The reason for this can be explained by the fact that increasing the canyon from
$AR = 1$ to 3 increases vertical ventilation (Blackman et al., 2015). An increase in sweep and ejection events would increase vertical ventilation. The larger canyon $AR$ allows for a more dynamic flow environment. For the C3h configurations it can be clearly observed that upstream roughness affects sweeps and ejections and has a smaller effect on the inward and outward interactions (refer to Figs. 33 and 34). It can be concluded that $AR$ significantly influences the average size of the quadrant event. For C1h there appears to be a “squashing” effect imposed by the canyon width on the quadrant events. This “squashing” effect was also observed by in the two-point correlations of the fluctuating velocities. This effect is not present in C3h canyons, where increasing the canyon $AR$ results in the geometry of the quadrant event being elongated in the streamwise ($x$) direction. Referring to Figs. 33 and 34, it can be observed that the shape of the inward and outward interactions present in C3h is symmetric in the $x$ and $y$ axis. For the Q2 events, the shape of the inward and outward interactions was found to be asymmetric in the $x$ and $y$ axis, by being elongated in the spanwise ($y$) direction. This could be due the previously mentioned squashing effect present in the street canyon. A summary of the sizes of the quadrant events for the unfiltered data can be found in Fig. 35 where the differences between R1h and R3h configurations can be clearly seen. The larger ejection events present throughout all configurations can be attributed to flushing motions present inside the street canyon (Takimoto et al. 2011). The present quadrant analysis shows that ejection events (Q2) make up most the vertical flushing motions in the street canyon and that the average size of the flushing event is highly influenced by canyon $AR$ and upstream roughness. The C1hR1h stands as an exception, where the thin high-frequency shear layer present in the skimming flow regime is the cause for reduced flushing motions. Perret et al. (2016) suggested that the shear layer formed at roof-level at the edge of the upstream building was responsible for strong ejections and penetrations in the street canyon.
Figure 34: The correlations contours of quadrant events in the C3h canyon where a cut-off of 0.4 is used to approximate the average size of the event. a) C3hRcu b) C3hR1h c) C3hR3h.
The same quadrant analysis can be conducted on the large-scales \((u'_x)\) and small-scales \((u'_z)\) using Eq. 5. The sizes of the small-scale and large-scale quadrant events are summarized in Fig. 36 and Fig. 37 for the small-scale and large-scale quadrant events sizes, respectively. Contour plots for the large- and small-scale quadrant events can be found in Appendix A. In Fig. 36 the small-scale spanwise sizes of the quadrant events are smaller than the raw unfiltered data (Fig. 35). Referring to Fig. 37 it can be observed that quadrant events occupy most of the measurement region in the spanwise \((y)\) direction, which is expected as the size of the spanwise filter is \(\Delta/h = 4.5\). There appears to be no influence of roughness and canyon on the large-scale spanwise \((y)\) structure of the quadrant events. This could suggest that large-scale quadrant events are not influenced by upstream roughness and canyon \(AR\). The small-scale quadrant events were found to have averages sizes slightly smaller than their unfiltered counterparts. The R3h configurations were found to have larger small-scale quadrants than R1h configurations. The present results show that there is a multi-scale behaviour present in the spanwise structure of quadrant events at roof-level of the street canyon flow. This complements the results of the second chapter, which suggested that there is multi-scale behaviour in the spanwise direction, from analysing two-point correlations. The clear difference between the size of the major- and minor-axis of the quadrant events of R3h and R1h configurations could be explained by the corresponding levels of amplitude modulation found by Blackman et al. (2018) for the same configurations. Perhaps, the average size of flushing events (identified by Q2) are a result of high modulations of small-scales by the large-scales. The spanwise variation of the flushing events suggests that there is a spanwise component to the mechanism of scale-modulation.
Figure 35: The spanwise and streamwise lengths of the average quadrant events for the unfiltered data, $Q_i$. a) Spanwise ($y$) length – C1h b) Streamwise ($x$) length – C1h c) Spanwise ($y$) length – C3h d) Streamwise ($x$) length – C3h

Figure 36: The spanwise and streamwise lengths of the average small-scale quadrant events, $Q_{il}$. a) Spanwise ($y$) length – C1h b) Streamwise ($x$) length – C1h c) Spanwise ($y$) length – C3h d) Streamwise ($x$) length – C3h
3.3.3 Large- and small-scale interactions

The previous sections have presented results from quadrant analysis, spanwise filtering, scale-separation and spatio-temporal correlations to quantify the large- and small-scales in the flow. The objective was to demonstrate that there is multi-scale behaviour in quadrant events and that imprints of large-scale structures above can be found in the street canyon, especially for the spanwise component. It was noted that canyon $AR$ and upstream roughness significantly affect the of correlations and geometry of quadrant events. The present section seeks an explanation for the relationship between large-scale and small-scale motions and quadrant events.

A sequence of snapshots of the flow over the C1hR3h configuration for unfiltered, large-scale and small-scale streamwise velocity fluctuations and large and small-scale sweep (Q4) events are presented in Fig 38. Fig 38b. reveals meandering positive and negative large-scale streamwise turbulence resembling a channelling effect. Hutchins and Marusic.
(2007) and Hutchins et al. (2011) found that meandering positive and negative streamwise velocity fluctuations represented large meandering superstructures in the boundary layer. The positive and negative variations of the streamwise fluctuating component at roof-level of the street canyon could be an imprint of the meandering superstructures above, resulting in a channelling motion. The canyon flow is channelled to the left or right; these motions could be triggered by meandering superstructures above.

Referring to Fig 38d., a high value of \( u'_s^2 \) indicates significant small-scale modulation. It can be observed that the regions of significant large-scale fluctuations generally correspond to greater small-scale fluctuations. This could suggest that the near-wall small-scale turbulence is being influenced by the meandering superstructures above (Hutchins and Marusic, 2007 and Hutchins et al., 2011). Inagaki and Kanda (2010) found very large streaks of low-momentum regions (measured at \( z/h = 2 \)) and, in the present work large-regions that streaks of low-momentum flow are also found, spanning the width of the canyon (for both C1h and C3h canyons). Inagaki and Kanda (2010) found that the low frequency modes of the spanwise component displayed a meandering motion as reported in Hurchins and Marusic (2007). Perret and Ruiz (2013) found the spanwise component to be influenced by the meandering motion of VLSMs. In the present work it can be observed that the spanwise component is exhibiting similar behaviour. Referring to Fig. 39 it can be seen that the large-scale spanwise velocity fluctuations follow a meandering pattern. This behaviour is consistent with Blackman and Perret (2016), where a canyon with an \( AR = 0.7 \) was used. This behaviour is not seen in the spanwise small-scale velocity fluctuations, suggesting that the positive to negative channelling motions are only present in the large-scales. Perret et al. (2016) analysed the iso-surfaces of the time evolutions of the fluctuating spanwise component, they found large-scale structures present in both space and time. The low-frequency coherent fluctuations were found to occupy the majority of the canyon cross-section.

The upstream roughness and canyon \( AR \) also have an impact on the large- and small-scale interactions. In the present work roughness was found to influence the large-scale spanwise motions, with the wake-interference (R3h) flow regimes having stronger channelling motions than the skimming flow regimes (R1h). The effects of roughness and
canyon $AR$ on the mean turbulent statistics (Blackman et al. 2015), the spanwise two-point space-time correlations, the integral length-scales and the scale modulation (Blackman et al. 2018) are consistent with the present results.

Referring to Fig. 39, it can be observed that sweep (Q4) events correspond to high-momentum regions ($u' > 0$). It was also found that ejection events (Q2) corresponded to low-momentum regions ($u' < 0$). Takimoto et al. (2011) found similar behaviour above the canyon and noted that almost half of the flushing events (indicated by mainly Q2 events) were observed at the same time as low-momentum regions. Michioka et al. (2010) observed that same behaviour of ejection events being linked to low-momentum regions at roof-level. The present work shows that this behaviour continues in the spanwise direction of the street canyon, often taking the entire later width ($6h$). The intermittent and multi-scale behaviour of flow near roof-level observed by Cui et al. (2004) is also observed in the spanwise direction. The low-momentum regions are frequently spawned with packets of hairpin vortices which involve ejection events within their structure (Zhou et al. 1999). Further investigations are needed to make a definitive conclusion if whether this model is applicable for roughened wall flows, however the evidence suggests that the model is appropriate. Coceal et al. (2007) was able to visualize similar hairpin-pin vortices near large-scale low-momentum regions over a cube roughness array. The presence of strong upward flow in organized structures over roughed walled flows is similar to the ones present in flows over smooth surfaces (Coceal et al., 2007; Inagaki and Kanda 2010). To further investigate this problem and to gain a more 3D understanding of the these mechanisms, more spanwise measurements would need to be conducted at various heights to understand the turbulent transport and the large- to small-scale interactions in street canyon flows.
Figure 38: A sequence of snapshots of a) unfiltered streamwise fluctuating velocities b) large-scale fluctuating velocities c) large-scale sweep (Q4) events d) small-scale fluctuating velocities e) small-scale sweep (Q4) events. Configuration displayed: C1hR3h (wake-interference flow regime). Time is denoted by $t$. $N = 1$ to 100 realizations are presented.

Figure 39: A sequence of snapshots of a) unfiltered spanwise fluctuating velocities b) large-scale spanwise fluctuating velocities c) small-scale spanwise fluctuating velocities. Configuration displayed: C1hR3h (wake-interference flow regime). Time is denoted by $t$. $N = 1$ to 100 realizations are presented.
3.4 Summary

Horizontal measurements were conducted at near roof-level in a street canyon using particle image velocimetry in a wind tunnel, for six configurations, consisting of three upstream roughness configurations and two canyon aspect ratios.

An analysis of available PIV data was used to investigate quadrant events, spanwise filtering and space-time correlations. The following was observed:

a) The upstream roughness was found to significantly affect the unfiltered spanwise spatio-temporal correlations for both C1h and C3h canyons. The wake-interference (R3h) configurations showed significantly higher correlations than the skimming flow cases (R1h). The spatio-temporal correlations of the streamwise ($R_{uu}$) and spanwise ($R_{vv}$) velocity fluctuations increased after a spatial filter ($\Delta / h = 4.5$) was applied, ascertaining that low-frequency motions could be present near roof-level of the street canyon. The substantial increase of the spatio-temporal correlation for the spanwise component suggests the presence of large-scale spanwise channelling motions in the flow at roof-level, which could possibly be an imprint of VLSMs and large-scale superstructures above, like those suggested by Hutchins and Marusic (2007) and Perret and Ruiz (2013). Blackman et al. (2018) noted that there is a significant difference between skimming flow and wake-interference flow regimes for the large- to small-scale modulation and the present results confirmed that this trend exists in the spanwise direction for space-time correlations.

b) It can be observed that the C3h configurations had a significantly higher (roughly two times) amount of sweep (Q4) and ejection (Q2) events than inward (Q3) and outward (Q1) interactions. The R3h upstream roughness configurations had the largest sweep (Q4) events, followed by Rcu and R1h. It was observed that roughness significantly affects the Q4 and Q2 events and had a smaller impact on the Q3 and Q1 events. It can be concluded that the
canyon $AR$ influences the average size of the quadrant events, such that for C1h a “squashing” effect was imposed on those events by the canyon width. This effect was not present in C3h canyons, where increasing the canyon $AR$ resulted in the geometry of the quadrant event being elongated in the streamwise direction. It was found that the average sizes of the flushing events were associated with high modulations of small-scales by the large-scales. The effects of roughness and canyon $AR$ imposed on the mean turbulent statistics (Blackman et al. 2015), the spanwise two-point space-time correlations, the integral length-scales and the scale modulation (Blackman et al. 2018) are consistent with the trends in quadrant events presented here.

c) Positive and negative streamwise velocity fluctuations were found, indicating large meandering superstructures in the boundary layer, noted previously by (Takimoto et al. 2011). The positive and negative variations of the streamwise fluctuating component at roof-level of the street canyon are thought to be an imprint of the meandering superstructures above. It was observed that sweep (Q4) events corresponded to high-momentum regions ($u' > 0$) and that ejection events (Q2) corresponded to low-momentum regions ($u' < 0$). Takimoto et al. (2011) found similar behaviour and noted that almost half of the flushing events (indicated by Q2 events) were observed at the same time as low-momentum regions. In the present work the size of the flushing events was found to extend over the entire measurement region in the spanwise direction ($6h$). The flow at roof-level in the street canyon was found to be highly intermittent, where sweep and ejections often lasting for up to $t u* / h = 10$. Spanwise variation in the quadrant events was also observed, which is considered to be influenced by the large-scale meandering structures above.
3.5 Conclusion

This chapter investigated the spatio-temporal structure of the flow, the quadrant events and small- and large-scales of turbulence present at roof-level of the street canyon. It was concluded that the upstream flow regime and canyon aspect ratio influence the instantaneous flow events. The large-scale structures, which are present above in the boundary layer, are believed to influence the instantaneous flow events present in the street canyon.

3.6 References


Chapter 4

Conclusions and Recommendations

This chapter presents the conclusions and recommendations from the present work of an experimental study on turbulent street canyon flows. Recommendations regarding the experimental procedure and the future work are included as well.

4.1 Conclusions

Understanding the spanwise structure of the flow and how it interacts with large-scale turbulent structures is necessary to reliably predict the mean pollutant transport in the lateral direction along the canyon and to further develop our knowledge on the 3D behaviour of turbulent street canyon flows. However, to the author’s knowledge there has not previously been a systematic study of the flow in a horizontal plane at canyon rooftop level. The two general objectives of this thesis were to investigate and characterize the spanwise variation of roof-level turbulence in a street canyon flow and to examine the instantaneous behaviour of the flow, gaining an insight into the spanwise organization of the turbulent structures. This was achieved using SPIV as a measurement technique to measure the flow at a horizontal plane near roof-level of the street canyon. The present thesis demonstrates that upstream roughness and street canyon width have a significant effect on the mean turbulent statistics, two-point correlations and integral length-scales.
The total turbulent kinetic energy and shear stress were found to be highest for the wake interference flow regimes and lowest for the skimming flow regimes. The attempt to broaden knowledge of the instantaneous behaviour of the flow established that roughness has a significant effect on the size of the quadrant events in the street canyon, with the wake-interference flow regimes producing significantly larger sweep and ejection events than the skimming flow regimes. Wake-interference flow regimes were found to have a greater temporal correlation than in the skimming flow regimes. It was found that there is an interaction between large- and small-scales at roof-level of the street canyon. The application of a spanwise filter revealed a larger spatio-temporal correlation for the spanwise fluctuating velocity component, which is an indication of larger scale structures above interacting with the roof-level region of the street canyon. Finally, ejection events were found to be coupled with low-momentum regions and sweep events with high-momentum regions. A cartoon illustrating the different flow structures and interactions present in a street canyon flow is displayed in Fig. 40. This thesis offers the following results:

a) The knowledge of the of the 3D behaviour of the flow is extended by characterizing the effect of roughness and canyon aspect ratio on the spanwise behaviour of the flow through mean turbulent statistics.

The roughness plan area density ($\lambda_p$) and $AR$ significantly affect the mean statistics at near roof-level of the street canyon. The mean streamwise velocity was highest for the skimming flow regime case (R1h), being larger than both the wake-interference (R3h) and 3D (Rcu) cases. Nevertheless, for the same $\lambda_p$ the 3D configurations yielded smaller streamwise velocities than the 2D configurations. The mean vertical velocity was found to be lower in the C1h canyon than the C3h configurations, suggesting a lower level of vertical ventilation for smaller canyons at roof-level. Wake interference flow regimes were found to have the highest levels of shear stress and skimming flow regimes the lowest. Increasing the canyon $AR$ yielded higher values of shear stress. Similar results were previously observed by Salizzoni et al. (2011), Michioka and Sato (2012) and Blackman et al. (2015).
There is a variation of the spanwise and streamwise two-point correlations and integral length-scales with the roughness plan area density ($\lambda_p$) and $AR$. In the street canyon, the two-point correlations were symmetrical for all quantities in the spanwise direction. Stronger correlations were found for the 2D roughness arrays than in the 3D arrays and the planform packing density ($\lambda_p$) was found to have no effect on spanwise correlations. It was found that the correlation decay in the streamwise direction was related to shear layer boundaries such that the configurations with the thickest shear layer had the strongest correlation. The integral length scales ($L_{uu}$) were found to be smaller for 3D than 2D flows in the spanwise direction. The integral length scales for vertical velocity fluctuations ($L_{ww}$) were found to be approximately three to four times smaller than $L_{uu}$. The ratio of the vertical integral length scales was found to be larger in the C3h cases, which could be due to larger turbulent structures at near roof-level in the C3h than the C1h configurations.

There exists a spanwise variation in the time-averaged mean structure of the flow. The upstream roughness and canyon $AR$ significantly alter the structure of the flow. The negative values of $R_{ww,x}$ could indicate organized vortex shedding. In the C1h configurations, negative values of $R_{ww,x}$ are only observed for R1h and this could be related to the stronger flapping of the shear layer than in the R3h and Rcu configurations. The circular radius of the two-point correlations suggests that the small-scales in the flow are rather isotropic and that their size depends on the upstream roughness configuration. Stronger spanwise correlations present in the R3h configurations suggests that wake-interference could be linked to larger spanwise flushing events in the street canyon. Elongated correlation structures in the streamwise direction for C3h configurations were found, while the structure of the correlation was elongated in the spanwise direction for the C1h configurations. The large-scale spanwise organization of the flow suggested by Perret et al. (2016) was also confirmed here by the strength of the correlations in the spanwise direction, notably for the C3h configurations.
b) The flow structures and mechanisms of the turbulent momentum transport and the interaction between the small-scales of turbulence generated by the roughness and the large-scales present in the boundary layer above have been investigated.

**The upstream roughness and canyon AR have a significant impact on the size of mean quadrant events.** The C3h configurations had a significantly higher amount of sweep (Q4) and ejection (Q2) events than inward (Q3) and outward (Q1) interactions. The R3h upstream roughness configurations had the largest ejection (Q2) events, followed by Rcu and R1h. It was observed that roughness significantly affects the Q4 and Q2 events and had a smaller impact on the Q3 and Q1 events. A “squashing” effect was also found to be imposed by the canyon width on the size of the quadrant events. This effect was not present in C3h canyons, where increasing the canyon AR resulted in the geometry of the quadrant event being elongated in the streamwise direction. It can be concluded that the canyon AR influences the average size of the quadrant events. It was suggested that the average size of flushing events (indicated by Q2 and Q1 events) was a result of high modulations of small-scales by the large-scales. The spanwise variation of the flushing events suggests that there is a spanwise behaviour in the mechanism of scale-modulation. The effects of roughness and canyon AR imposed on the quadrant events are consistent with the trends present in the mean turbulent statistics (Blackman et al. 2015), the spanwise two-point space-time correlation and the scale modulation (Blackman et al. 2018).

**Imprints of large-scale motions were found at roof-level of the canyon.** Positive and negative streamwise velocity fluctuations were found at roof-level of the street canyon. This indicates large meandering superstructures in the boundary layer. The positive and negative variations of the streamwise fluctuating velocity component at roof-level of the street canyon are thought to be an imprint of the meandering superstructures above. Sweep (Q4) events corresponded to high momentum regions \( u' > 0 \) and ejection events (Q2) corresponded to low-momentum regions \( u' < 0 \). In the present thesis, the size of the flushing events was found to take up to the entire spanwise length of the measurement region \( 6h \). The sweep and ejections often lasting up to \( 10h / u_* \), showed the flow at roof-level in the street canyon is highly intermittent. The spatio-temporal correlations of
the streamwise ($R_{uu}$) and spanwise ($R_{vv}$) velocity fluctuations increased after a spatial filter ($\Delta / h = 4.5$) was applied, ascertaining that low-frequency motions could be present near roof-level of the street canyon. The increase of the spatio-temporal correlation for the spanwise component suggests the presence of large-scale spanwise channelling motions in the flow at roof-level, which could possibly be an imprint of large-scale superstructures above, like those suggested by Hutchins and Marusic (2007) and Perret and Ruiz (2013).

Referring to Fig. 40, the modulation of small-scales by the large-scale structures in the boundary layer are present in both cases. A systematic investigation of roof level scale-modulation was not conducted in the present thesis however, Blackman et al. (2018) found an influence of upstream roughness geometry on the non-linear interactions between the small-scales created by the roughness and the large-momentum regions above. The wake-interference flow regime was found to have more scale modulation present than in the skimming flow regime. The blue arrows in Fig 40. represent spanwise channelling motions that have also been observed in Perret et al. (2016). Large-scale meandering superstructures above are represented by wavy blue lines. The present work did not directly measure meandering motions, low- and high-momentum regions above in the boundary layer, however it is hypothesized that they influence the channelling motions at roof level.
Figure 40: Pictorial cartoons of the interaction of the turbulent structures present at roof-level of the street canyon and the boundary layer above. a) Skimming flow regime (R1h) b) Wake-interference flow regime (R3h).
4.2 Contributions

The present thesis showed that there exists a spanwise variation of roof-level turbulence in a rectangular street canyon model which is a simplified representation of many urban street configurations. This thesis brings forth the following contributions:

- There had not previously been a systematic study of the flow in a horizontal plane at canyon rooftop level. The present thesis provides useful information on the behaviour of the flow within a street canyon, used here as a simpler model to investigate the characteristics of the flow existing in one or several neighbouring streets within an urban area by removing the complexity induced by the presence of intersections. It can be concluded that there is a spanwise variation in the turbulence at roof-level which is dependent on characteristics of the upstream flow and canyon geometry. The new knowledge of flow in the spanwise direction provides insight on the statistical spatial structure of the mechanism driving vertical momentum transport between the street canyon and the overlying boundary layer. The present results clearly show the impact of both the canyon and upstream roughness configuration on the structure of the flow at roof level, the former being not the sole factor influencing the dynamics of the momentum exchange in this region.

- The instantaneous behaviour of the flow near-roof level of the street has been shown to be affected by upstream roughness and the canyon width. The spanwise structure and size of intermittent flushing events have been shown to vary with different configurations. The present thesis suggests that the presence of large-scale superstructures in the boundary layer above influence the flow in the street canyon, such as spanwise channeling motions. It was found that there is an interaction between large- and small-scales at roof-level of the street canyon. In general, the present thesis demonstrates that there is coupling of momentum, large- and small-scales motions above and at roof-level of the street canyon.
4.3 Recommendations for future work

The author would like to provide the reader with the following recommendations for future research:

- Further investigation of the basic scale-interaction mechanism for different types of boundary layers, to provide a foundation upon which a general model for the flow dynamics in the street canyon can be developed.
- Further understanding instantaneous spatial organization of the turbulent structures present in the flow and how it relates to the scale interplay and exchange.
- Quantifying spanwise channelling motions and understanding their relationship to the shear layer and the incoming boundary-layer.

The author would like to provide the reader with the recommendations for the methodology for future research:

- The precise height of the laser should be determined by comparing turbulent statistics with previous data if available. Turbulent statistics change rapidly with height near-roof level of the street canyon, therefore care needs to be taken in determining the proper height of the laser sheet.
- To further investigate this problem, it is recommended that more spanwise measurements should be conducted over various heights to understand the turbulent transport and the large to small-scale interactions in street canyon flows and to gain a more 3D understanding of the these mechanisms.
- Conducting experiments at higher PIV sampling frequencies would allow for higher temporal resolution thus more information on the small-scale behaviour of the flow.
- Introducing more realistic roughness arrays which contain buildings significantly taller than the canyon ( > 5h ) to see if the turbulent transport mechanisms are still present.
4.4 References


Appendix A

Quadrant analysis

Quadrant events were used as conditional filters at the centre point \((x = 0, y = 0)\) of the measurement plane. The objective of this filter is to investigate sweep and ejection events which are primarily responsible for momentum transfer in the flow over a rough surface and are contained in the elongated superstructures that meander in the horizontal plane (Perret and Ruiz, 2013). The mean spanwise velocity conditionally filtered for an ejection event (Q2) is plotted along the spanwise centre-line of the street canyon and is presented in Fig. A-1. The spanwise mean velocity profiles reach zero at the centre point due to conservation of mass and momentum. It can be observed that the upstream roughness and canyon geometry have a significant effect on the magnitude of the mean spanwise velocity at this position. The C3h configurations were found to have higher mean spanwise velocities near the convergence point than the C1h configurations. In the C1h canyon, C3h roughness configurations were found to have the highest velocities near the convergence points followed by the Rcu and R1h configurations. The effect of roughness on the profiles is less present for the R3h canyons (Fig. A-1b), which could be due to the larger canyon \(AR\) affecting the mean turbulence statistics more than the roughness. Results from Ch.2 found a similar trend in the two-point correlations and integral length scales of the spanwise fluctuating velocity \(R_{vv,y}\) and \(L_{vv,y}\), respectively) in the spanwise
direction (y) over the same flow configurations. This suggests that the strength of a local ejection or sweep is proportional to the strength of the spanwise correlation in the street canyon. Decreasing the packing density and changing the roughness from 2D to 3D increases the spanwise velocities approaching the convergence point (x = 0, y = 0).
Figure A - 1 Profiles of the spanwise time-averaged mean velocity profiles conditionally filtered at the centre-point \((x = 0, y = 0)\) by an ejection event (Q2), plotted on the spanwise centre-line \((x = 0)\) of the street canyon.
The boundaries of each quadrant event for are presented in Figs A-2 to A-5. The boundary was computed using the same method as in Ch. 3. The boundaries of the quadrant events for the C1h canyon are presented in Figs. A-2 and A-3, for the small-scale and large scale events, respectfully. The boundaries of the quadrant events for the C3h canyon are presented in Figs. A-4 and A-5, for the small-scale and large-scale events, respectively. Contour plots of the mean spanwise velocity normalized by the freestream velocity ($\overline{V_f} / U_e$), conditionally filtered at centre-point ($x = 0, y = 0$) by an ejection event (Q2) are presented in Fig. A-6 and A-7, for C1h and C3h, respectively. Fig. A-8 presents the relative contribution of each quadrant event to the frequency of occurrence for 400 samples.

a)

![Correlation contours of small-scale quadrant events](image)

b)

![Correlation contours of small-scale quadrant events](image)

c)

![Correlation contours of small-scale quadrant events](image)

Figure A - 2 The correlation contours of small-scale quadrant events where a cut-off of 0.4 is used to approximate the average size of the event. a) C1hRcu b) C1hR1h c) C1hR3h.
The correlation contours of large-scale quadrant events where a cut-off of 0.4 is used to approximate the average size of the event. a) C1hRcu b) C1hR1h c) C1hR3h.
Figure A - 4 The correlation contours of small-scale quadrant events where a cut-off of 0.4 is used to approximate the average size of the event. a) C3hRcu b) C3hR1h c) C3hR3h.
Figure A - 5 The correlation contours of small-scale quadrant events where a cut-off of 0.4 is used to approximate the average size of the event. a) C3hRcu b) C3hR1h c) C3hR3h.
Figure A - 6 Contour plots of the mean spanwise velocity normalized by the freestream velocity ($\overline{V} / U_e$), conditionally filtered at the centre-point ($x = 0, y = 0$) by an ejection event (Q2) a) C1hRcu b) C1hR1h c) C1hR3h.
Figure A - 7 Contour plots of the mean spanwise velocity normalized by the freestream velocity ($\bar{V}_f / U_e$), conditionally filtered at the centre-point ($x = 0, y = 0$) by an ejection event (Q2) a) C3hRcu b) C3hR1h c) C3hR3h.
Figure A - 8 The relative contribution of each quadrant event to the frequency of occurrence for 400 samples. a) C1hRcu b) C1hR1h c) C1hR3h.
References

Appendix B

Two-point space-time correlations

This appendix contains space-time correlations of spatially filtered and unfiltered data for all the configurations which were not included in chapter 3 (total of four configurations). They can be found in Figs. B-1 to B-4.
Figure B - 1 3D surface plots of the spanwise space-time correlations for unfiltered and filtered data, a) $R_{uu}$ – unfiltered b) $R_{uu}$ – filtered c) $R_{vv}$ – unfiltered d) $R_{vv}$ – filtered e) $R_{ww}$ – unfiltered f) $R_{ww}$ – filtered. Configuration shown: C1hRcu.
Figure B - 2 3D surface plots of the spanwise space-time correlations for unfiltered and filtered data, a) $R_{uu}$ – unfiltered  b) $R_{uu}$ – filtered  c) $R_{vv}$ – unfiltered  d) $R_{vv}$ – filtered e) $R_{ww}$ – unfiltered  f) $R_{ww}$ – filtered. Configuration shown: C3hRcu.
Figure B - 3D surface plots of the spanwise space-time correlations for unfiltered and filtered data, a) $R_{uu}$ – unfiltered  b) $R_{uu}$ – filtered c) $R_{vv}$ – unfiltered  d) $R_{vv}$ – filtered e) $R_{ww}$ – unfiltered  f) $R_{ww}$ – filtered. Configuration shown: C3hR1h.
Figure B - 4 3D surface plots of the spanwise space-time correlations for unfiltered and filtered data, a) $R_{uu}$ – unfiltered  b) $R_{uu}$ – filtered c) $R_{vv}$ – unfiltered d) $R_{vv}$ – filtered e) $R_{ww}$ – unfiltered f) $R_{ww}$ – filtered. Configuration shown: C3hR3h.
Appendix C

Experimental error analysis

The present Appendix contains the details of the error analysis and the convergence of the mean turbulent statistics. Refer to Tropea et al. (2007) for further details on the experimental uncertainties. The statistical error of the turbulence quantities is to quantify the error.

The statistical errors were calculated on a single point in the measurement region. The centre \((x = 0, y = 0)\) of the measurement region was used. Samples are statistically independent as they were separated by a period of two-times the integral time scale. The number of significant samples in the present work was: 2551. The computation of the number of independent samples is presented in Eq. C1, where \(T\) denotes the measurement time and \(T_x\) the integral time scale. The convergence graphs for the mean velocity, standard deviation and variance are presented in Figs. C-1 to C-4 for, \(x\), \(y\) and \(z\) components, respectively.

\[
N = \frac{T}{2T_x}
\]  
(C1)
The standard deviations of the mean velocity, standard deviation and Reynolds shear stress are presented in Eqs. C2-C4, respectively. The present work the standard deviations of the statistics are normalized by the corresponding statistic at the centre. For example, the standard deviation of the Reynolds shear stress would be normalized by the Reynolds shear stress at the centre of the measurement region. The expressions presented in Eqs. C2-C4 all assume statistical independence between all samples. Furthermore, it should be mentioned that all turbulence quantities are assumed to be normally distributed. 

\[
\sqrt{\frac{\sigma_{\bar{u}}^2}{N}} \quad \text{(C2)}
\]

\[
\sqrt{\frac{\sigma_{\bar{u}}^2}{2N}} \quad \text{(C3)}
\]

\[
\sqrt{\frac{\sigma_{\bar{u}}^2 \sigma_{\bar{w}}^2 + (\bar{u}'\bar{w}')^2}{N}} \quad \text{(C4)}
\]
Figure C - 1 Convergence graphs for the streamwise ($x$) component of the a) Mean velocity (m/s) b) Standard deviation (m/s) c) Variance (m/s) d) Skewness (m/s).
Figure C - 2 Convergence graphs for the spanwise ($y$) component of the a) Mean velocity (m/s) b) Standard deviation (m/s) c) Variance (m/s) d) Skewness (m/s).
Figure C - 3 Convergence graphs for the vertical (z) component of the a) Mean velocity (m/s) b) Standard deviation (m/s) c) Variance (m/s) d) Skewness (m/s).
Figure C - 4 Convergence graph for the Reynolds shear stress (m/s)$^2$.

References

Curriculum Vitae

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