Twin wind tunnel investigation of the scale effects on a street canyon flow

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SUMMARY:
An investigation of the scale effects when studying urban street canyon flows is carried out in two wind tunnels. The examined model is a series of five identical street canyons, perpendicular to the approaching flow, simulating an urban environment. The study focuses on the fourth canyon with respect to the direction of the flow. The height-to-width and the length-to-width aspect ratios of the street canyons are 1 and 8, respectively. Three-dimensional particle tracking velocimetry (3D-PTV) and pressure measurements were conducted in the closed-loop wind tunnel of the National Technical University of Athens (NTUA) as well as the open jet facility (OJF) of TU Delft. Comparative results for the velocity indicate that Reynolds number independence (RNI) is satisfied for $Re = 30000$. However, the surface pressure results indicate that Reynolds numbers within the range (60000, 100000) may be necessary to achieve RNI.

Keywords: Urban Street Canyon, 3D Particle Tracking Velocimetry, Scaling Effects

1. INTRODUCTION

The street canyon geometry is one of the basic structural components of contemporary cities. This geometry is linked to an increased pollutant entrapment (Li et al., 2006) at the pedestrian level, a situation which is more pronounced when the wind direction is perpendicular to the canyon. For this orientation, three distinct flow regimes, depending on the height-to-width (H/W) ratio of the canyon, are distinguished: (i) skimming flow, (ii) wake interference and (iii) isolated roughness regime (Li et al., 2006). A case in the skimming flow regime ($H/W = 1 > 0.65$) is investigated here mainly for two reasons: (a) it corresponds to the worst-case scenario regarding the pollution at pedestrian level (Li et al., 2006), and (b) most of the research involving street canyons focuses on this kind of geometry, commonly with an aspect ratio $AR = 1$ (e.g. Dsouza et al., 2024; Gromke and Ruck, 2009). The length-to-width ratio was chosen as $L/H = 8 > 7$ ensuring the development of a 2D region around the plane of symmetry (Hunter et al., 1990). The series of five canyons (six building blocks) ensures that the flow is in the urban roughness regime (Meroney et al., 1996).

It is often difficult to attain the value of the full-scale Reynolds number in wind tunnel testing (reduced-scale). To circumvent this, Reynolds Number Independence (RNI) has to be established at lower, achievable Reynolds numbers in wind tunnels. Although Chew et al. (2018) found that a

Reynolds number of $Re = 12000$ establishes RNI for urban street canyons with $AR = 1$, Shu et al. (2020) found that RNI is more difficult to achieve for regions close to the walls of the canyon. Dsouza et al. (2024) also examined scaling effects in both three-dimensional (near the one end of the canyon) and two-dimensional regions of a street canyon geometry, by employing 3D Particle Tracking Velocimetry (3D-PTV). They observed RNI within the range Re=13000, 17000 for the mean quantities but not for turbulence quantities. Following previous works and the suggestion of locally varying RNI (Shu et al., 2020), the present study examines a wide range of Reynolds numbers (i.e. $24000 \leq Re \leq 100000$) and aims to complement existing data and observations. Measurements in two wind tunnels provide localised information on 2D and 3D mean and higher order statistics of velocity. Surface pressure distributions on the center plane are also measured, being of interest in building air exchange rate and wind force calculations.

2. EXPERIMENTAL CONFIGURATION

3D-PTV and pressure measurements were conducted in the closed-loop wind tunnel (WT) facility of the National Technical University of Athens (NTUA). The dimensions of the test section were 3.5×2.5×12.1 m, with minimum attainable turbulence intensity $\sim 2\%$.
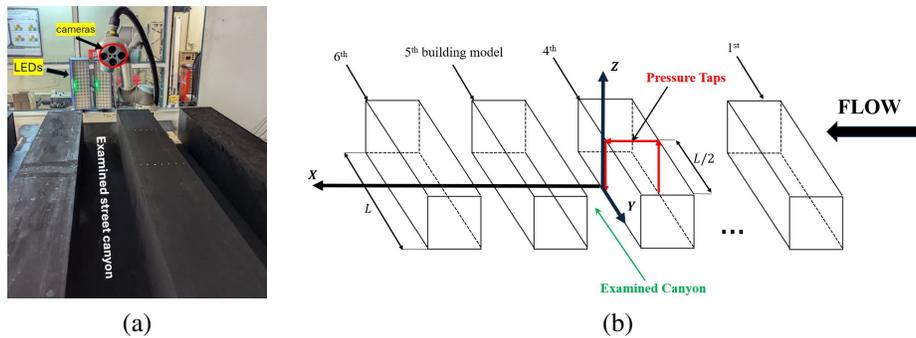

(a)   (b)

Figure 1. (a) Experimental setup using TU Delft's Coaxial Volumetric Velocimetry (CVV) probe mounted on a Universal Robots UR5 robotic arm at NTUA's facilities. (b) Schematic illustration of the utilised model, its orientation and geometry (not all canyons are shown).

A Universal Robots UR5 robotic arm with six degrees of freedom was used for the PTV measurements. A coaxial volumetric velocimetry (CVV) probe (Schneiders et al., 2018) consisting of four CMOS cameras with 4 mm objectives, had been mounted on the UR5 robotic arm. The specifications of the CVV system, can be found in (Dsouza et al., 2024). For the illumination, two LaVision LED Flashlight 300s were utilised while neutrally-buoyant Helium-filled soap bubbles (HFSB) were used as tracer particles (Faleiros et al., 2019). The acquisition frequency, the number of acquisitions and their duration were adjusted in order to capture at least 80 turnovers of the canyon vortex. The maximum acquisition frequency was $f = 727$ Hz. The equipment had been provided by TU Delft and had been already successfully used for experiments of the same geometry by Dsouza et al. (2024). A photograph of the experimental setup is given in Fig. 1a.

The model was mounted onto a splitter plate elevated from the wind tunnel floor to avoid boundary layer effects. A schematic illustration of the model is given in Fig. 1b. Pressure taps were installed on the fourth building model along the red line of the same figure ($Y = 0$), following the direction of the flow. A 60-channel FCS421 (Furness Controls Ltd) pressure scanner was used to connect the

tubing to a DP103 low pressure Validyne sensor (see Pallas et al., 2024, for details of the system).

The same configuration was also studied at the open jet facility (OJF) of TU Delft (cross section: 2.85×2.85, minimum turbulence intensity: ~1%). 3D-PTV measurements are still being processed and will be presented at the conference. A DSA3217/3218 Series Scanivalve Pressure Scanner (600 Pa pressure module, accuracy 0.1%) was used for the pressure measurements.

3. RESULTS

Contours of the normalised mean streamwise velocity component and velocity vectors are given for $Re = 30000$ and $Re = 60000$, in Fig. 2 for the centre-plane of the examined canyon at NTUA. The Reynolds number is defined as $Re = U_{Ref}H/\nu$ where U_{Ref} is the free-stream velocity, H is the height of the canyon and $\nu = 1.5 \times 10^{-5}$ m^2/s is the kinematic viscosity of air at 20° C. Overall, no significant differences are obvious between the results of $Re = 30000$ and $Re = 60000$, in Fig. 2, except some small differences in the lower left corner where the secondary vortex is observed. This was also corroborated by examining velocity and turbulent kinetic energy profiles along the centre-line of the plane of symmetry (i.e. for $X = 0.5$ and $Y = 0.5$), which are not shown here.
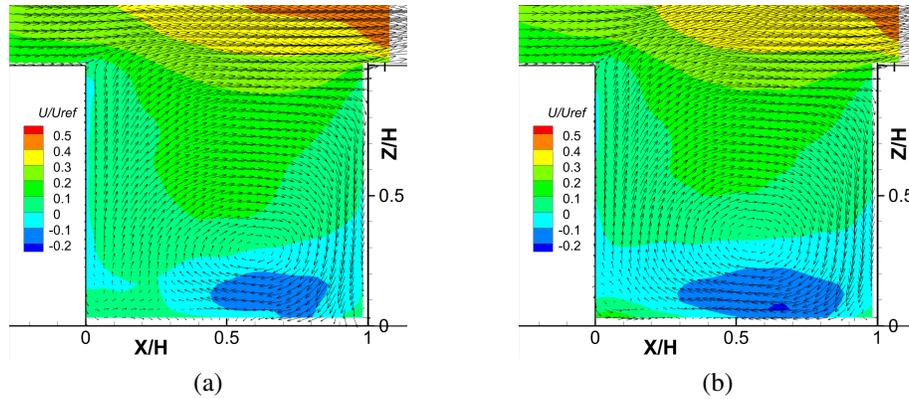

(a)   (b)

Figure 2. (a) Contours and velocity vectors of the normalised mean streamwise velocity component U/U_{Ref} for: (a) $Re = 30000$ and (b) $Re = 60000$, in the centre-plane.

Finally, surface pressures are shown in Fig. 3, measured along the red line of Fig. 1b. S/H accounts for the non-dimensional distance along the line, in the direction of the flow. The value located at $S/H = 1.04$ (first pressure tap on the roof) is used as a reference pressure for both measurement sets (NTUA and TU Delft). The differences in roof pressure values among the different Reynolds numbers are small for both of these sets. There is some small spread in the results within the canyon ($S/H = 0-1$ and $S/H = 2-3$) between $Re = 30000$ and $Re = 60000$ but for $Re > 60000$ a distinct group of curves arises in Fig. 3b, indicating that there are differences in surface pressures between $Re = 60000$ and $Re = 100000$ while for $Re = 80000$ and $Re = 100000$ the results coincide.

4. CONCLUSIONS

A twin experimental campaign investigating the scale effects in an urban street canyon has been carried out in the closed loop wind tunnel of NTUA and the open jet facility of TU Delft. Initial results presented here indicate that the non-dimensional velocities do not demonstrate significant
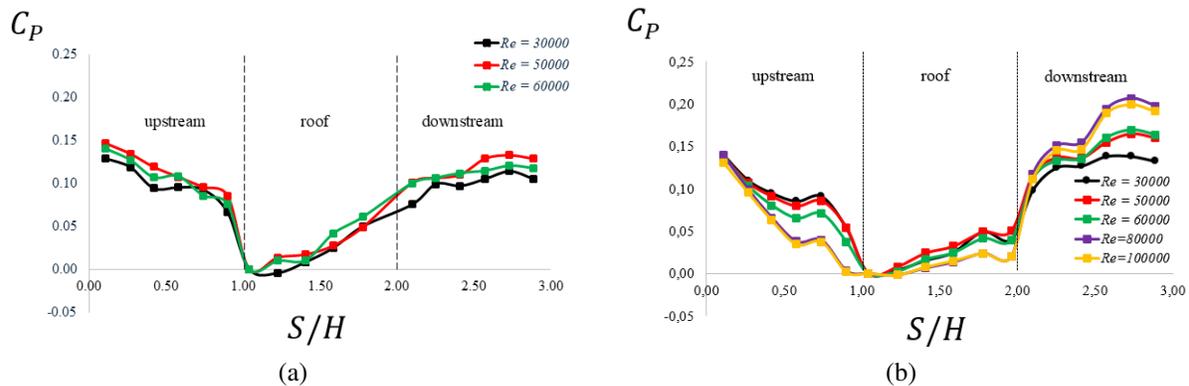
Figure 3. Surface pressure coeffcient profiles for different Reynolds numbers within the range: (a) [30000, 60000] (NTUA experiment) and (b) [30000, 100000] (TU Delft experiment).

differences for Reynolds numbers in the range [30000, 60000]. However, surface pressures show a tendency of satisfying Reynolds number independence (RNI) at a higher Re, namely $Re = 60000 - 100000$. This could also be an indication of local variability of RNI. Further results of velocity measurements at TU Delft and higher order statistics will be presented in at the conference.

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