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Towards Reliable CFD Validation from Wind Tunnel Studies of the Flow in a Street Canyon

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SUMMARY

Street canyons have been extensively studied in wind tunnels, using substantially different setups in terms of geometry and upstream flow. Although many in-canyon measurements are in agreement, despite differences in the setup, there are others where significant deviations are observed, although the geometrical configuration is the same. This poses a challenge both for the wind tunnel studies but also for CFD validation endeavors. To investigate the effective parameters, LES (3D) and RANS (quasi 2D) simulations of the flow in a street canyon are performed and compared against selected wind tunnel datasets. In this first step, the effect of canyon span to width ratio (L/W) is examined, while also focusing on the above canyon flow. Results indicate that the differences in the measurements cannot be clearly attributed to variations in the spanwise canyon dimension or the above canyon flow shear and that other parameters must also be investigated.

Keywords: *Street Canyon, Computational Fluid Dynamics, Validation, Large Eddy Simulation, Wind Tunnel*

1. INTRODUCTION

Urban street canyons are a fundamental flow unit for studying wind and pollutant transport in cities. Canyons with height to width ratio (H/W) of 1 are a simple yet representative benchmark geometry for wind tunnel and Computational Fluid Dynamics (CFD) studies. Several wind tunnel studies have examined flow in such street canyons. Kovar-Panskus et al. (2002) investigated a long isolated canyon (L/H=12.9) exposed to turbulence generated by a grid, vortex generators and fences while Allegrini et al. (2013) also studied an isolated canyon (L/H=9) in a closed-loop tunnel but with a thin upstream boundary layer. Uehara et al. (2000) used cubic blocks with a rough upstream atmospheric boundary layer (ABL) whereas Lin et al. (2021) embedded the target canyon within a 25-row array of buildings (L/W=10). All of these studies reported a single, centrally located recirculation cell within the canyon. In contrast, Cui et al. (2014), measured an off-centre vortex in a short canyon (L/W=3) exposed to a rough upstream ABL. 3D effects may be a factor but Hunter et al. (1990) had found that the spanwise velocity inside the canyon was effectively zero, even with L/W=7. Figure 1 shows that, despite differing experimental configurations, most datasets yield similar velocity profiles inside the canyon, except for the short canyon (L/W=3), where the flow also exhibits much higher shear at roof level. Indeed, in a recent LES study, Zhu and Chew (2025) observed that the above-canyon boundary layer shear is an important parameter and also showed that significant spanwise motion persist even for canyons with L/W=10.

The recent TWEET-IE twin test campaign (Pallas et al., 2025, Dsouza et al., 2025) involved PTV measurements in identical multi-canyon layouts and geometries (H/W=1, L/W=8) in two facilities (closed-loop NTUA, open-jet TU Delft). However, the mid-canyon vortex location differed markedly: a lower, windward-shifted vortex was measured at NTUA, while no recirculation was found at the mid-plane in TU Delft measurements. Intriguingly, one set of measurements from the TWEET-IE campaigns is in reasonable agreement with other studies in long canyons, even though the above-canyon flow has less shear (Figure 1). The TWEET-IE TU Delft measurements agree with those of the short (L/W=3) canyon (Cui et al., 2014), although these two datasets constitute the upper and lower limit of above-canyon shear. These observations demonstrate that spanwise geometry and/or above canyon flow characteristics may be strongly affecting the in-canyon vortex structure and raise significant challenges for CFD validation and full scale transferability. The present work applies LES and RANS simulations across different canyon spans (L/W=∞,8,4) to determine the effect of these factors on the flow structure and to establish a consistent basis for interpreting wind tunnel data in CFD validation.

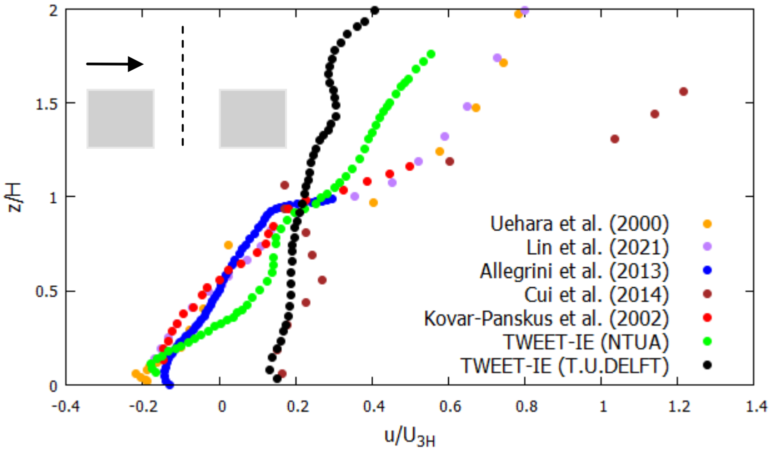

Figure 1: Comparison of Centerline Velocity Profiles from Reference Studies and TWEET-IE Measurements.

2. METHODS

The RANS simulations were performed with an in-house finite volume solver (Kotsiopoulou and Bouris, 2022) on a Cartesian collocated grid with the SIMPLE algorithm for pressure–velocity coupling and the RNG k-ε model for turbulence modelling. uDALES v2.0 (Suter et al., 2022), an open source Large Eddy Simulation (LES) framework for urban atmospheric flows was also implemented for 3D effects. The filtered incompressible Navier–Stokes equations are solved on a Cartesian grid with pressure obtained via FFT inversion and turbulence modeled with the Vreman subgrid-scale model (Vreman, 2004). u-DALES simulations were performed with three geometric configurations: (i) an infinite canyon, and a finite canyon with (ii) L/W=8, and (iii) L/W=4. The computational domain for all LES cases extended 4Hx24Hx8H in the streamwise (x), spanwise (y) and vertical (z) directions, respectively. The grid resolution was Δx=Δz=H/16 and Δy=H/8 (1.5M cells), leading to $y^+ \approx 23$ and the timestep satisfied Δt/T<1/1300, where T is the characteristic vortex-turnover time. Periodic inlet-outlet conditions were applied to represent a repeating canyon sequence, with periodic lateral boundaries and a free-slip condition imposed at the top of the domain. RANS simulations were conducted using an infinite (quasi 2D) canyon configuration, consistent with the implementation of Suter al. (2022). The mesh resolution inside the canyon was Δx=Δz=H/260 and Δy=H/10 and the computational domain was 3Hx0.5Hx5H (1M cells in total). The measured velocity profile at the roof of the 4th building was prescribed at the inlet to reproduce a fully developed street canyon flow consistent with the wind tunnel configuration. The RANS simulations employ standard wall functions with viscous and logarithmic subregions. In uDALES, a logarithmic wall function based on aerodynamic roughness length is used. The viscous sublayer is not explicitly resolved and a coarser near-wall grid is therefore appropriate. The LES grid resolution is consistent with the wall stress formulation and sufficient to resolve the large-scale structures. Preliminary refinement tests indicated insensitivity of the mean flow to further grid refinement. The simulations were performed at $Re_H=10^5$ and $5\cdot10^4$, respectively, well above the commonly accepted limit for Re independence of the mean flow.

3. RESULTS

The contours of streamwise velocity and the velocity vectors at the mid-canyon plane from the PTV measurements at NTUA and TU Delft are shown in Figure 2(a,b), together with the CFD results: u-DALES infinite canyon (Figure 2c), RANS infinite canyon (Figure 2d), u-DALES L/W=8 (Figure 2e) and L/W=4 (Figure 2f). The infinite canyon simulations (u-DALES and RANS) produce quite similar flow fields, featuring a well-defined single vortex centered within the canyon. In contrast, NTUA measurements show the vortex displaced downward and toward the windward wall, while in the T.U. Delft facility no clear recirculation emerges at the mid-plane, with predominantly upward flow observed. Reducing the canyon span in LES alters the vortex structure: for L/W=8 the vortex shifts upward and toward the leeward wall, whereas for L/W=4 it moves downward and downstream, similar to the NTUA measurements.

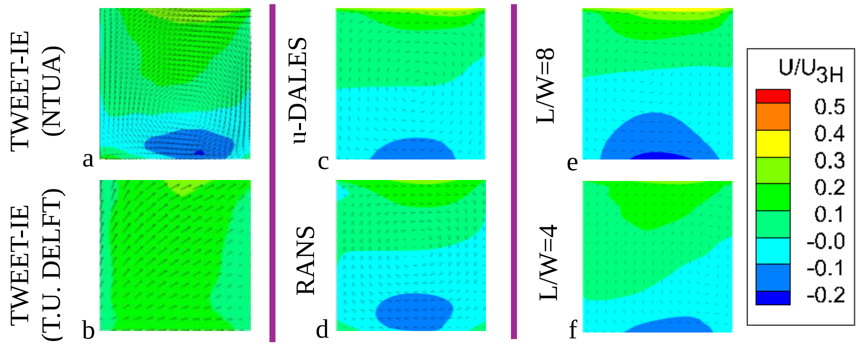

Figure 2: Streamwise velocity and velocity vectors at the mid-canyon plane from CFD and WT measurements.

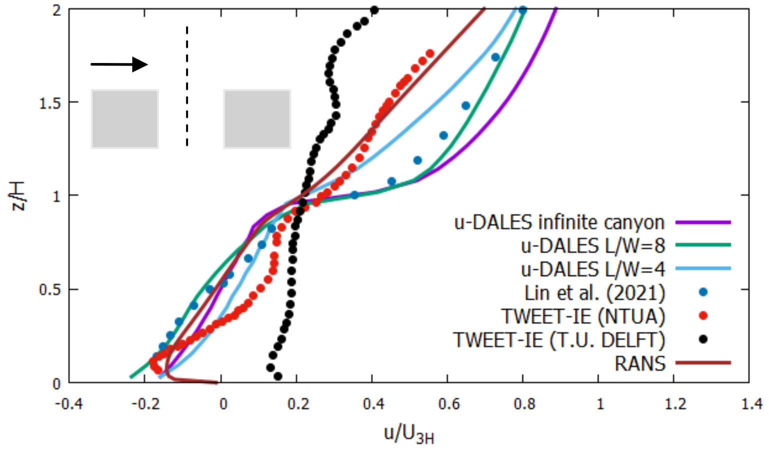

Figure 3: Comparison of Centerline Velocity Profiles from CFD and TWEET-IE Measurements.

Figure 3 presents the streamwise velocity profiles along the canyon centerline for the u-DALES (L/W=∞,8,4), the Lin et al. (2021) measurements and the TWEET-IE data. The L/W=∞,8 simulations agree well with Lin et al. (2021), within and above the canyon. The RANS infinite canyon solution reproduces Lin et al. (2021) profile within, but not above, the canyon, but aligns with the TWEET-IE NTUA profile in both regions. Overall the LES with L/W=4 yields the closest match to the TWEET-IE NTUA data, although L/W=8 for the measured canyon. Despite the consistent TWEET-IE configuration, the TWEET-IE TU-Delft measurements differ markedly from all CFD solutions or other measurements, both inside and above the canyon, indicating that the canyon length and above canyon flow, alone, cannot explain all the observed discrepancies.

4. CONCLUSIONS

This study examines the sensitivity of H/W=1 street canyon flow to several configuration factors, using LES and RANS simulations, focusing on the influence of canyon length (L/W=∞,8,4) and the flow above the canyon. The CFD results show that long-span configurations (L/W=∞,8) generally reproduce the canyon flow structure reported in the literature for isolated and urban canyons of similar length. However, simulations of shorter spans (L/W= 4) show a displaced primary vortex but don’t agree with measurements of similar spans or with recent TU-Delft data. Overall, there remains a need for explaining the differences in measurements and simulations of urban street canyon flow, based on parameters related to geometry and above-canyon flow. This highlights the need for careful interpretation of reference datasets when validating CFD models.

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