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Flow Topology and Reynolds Number Independence in an Urban Street Canyon using 3D Lagrangian Particle Tracking

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Abstract

We present a three-dimensional characterization of the flow inside an urban street canyon with an aspect ratio of unity, and a length-to-canyon-width ratio of 8, in the range of Reynolds numbers (based on building height) between 10,000 and 30,000. The measurements, performed by three-dimensional Lagrangian Particle Tracking, unveil the three-dimensional flow topology and enable the evaluation of the critical Reynolds numbers for both the time-average velocity and the Reynolds stresses. Our experimental investigation revealed that for a canyon with $L/W = 8$, a spanwise vortex is formed at the edge of the canyon, whose strength decreases as it approaches the center plane, and the vortex disappears completely at the center plane for all Reynolds numbers tested. The Reynolds number sensitivity analysis confirmed that the critical Reynolds number for mean streamwise velocity was at $Re = 10000$, whereas for the spanwise velocity component and circulation, it was found that Reynolds number independence was achieved at $Re = 17000$ and for the vertical velocity component, the critical Reynolds number was at $Re = 20000$. For the higher-order quantities, it was found that the critical

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Reynolds number was also around $Re = 17000$.

Keywords: Urban Street Canyon, Urban Aerodynamics, Lagrangian Particle Tracking, Flow Topology, Reynolds Number Independence

1. Introduction

An Urban Street Canyon is defined as a relatively narrow street lined by buildings on both sides (Jeong and Andrews [1]). Urban canyon flows are important in the field of urban comfort and air quality because urban canyons have a poor self-ventilating capability and therefore tend to trap heat and pollutants (Chew et al. [2], Britter and Hanna [3]). In the context of experimental urban aerodynamics, the geometry of an urban street canyon is often simplified to rectangular blocks of spanwise length L , height H , and canyon width W . The flow around an isolated building or block can be divided into three zones of disturbance (Oke [4]). A bolster vortex exists on the windward side of the building because of the boundary layer upstream of the building and the flow stagnation occurring on the windward face. A lee eddy is created at the leeward side because of the low-pressure region caused by the flow separation due to the sharp edges of the roof and sides. Further downstream, the unsteady wake of the building is characterized by higher turbulence levels and a streamwise momentum deficit (figure 1).

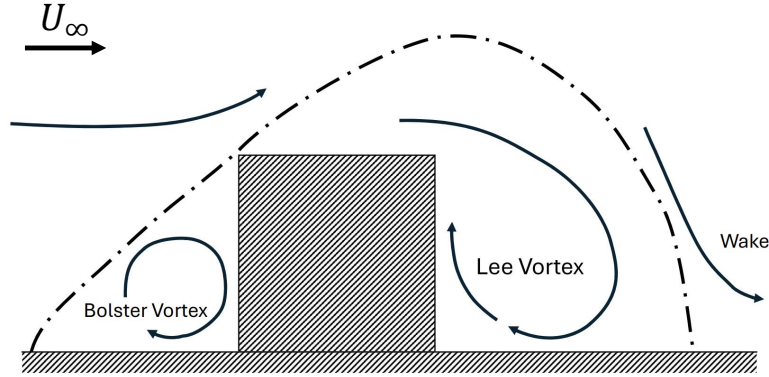


Figure 1: Flow field around an isolated building. Three distinct zones are visible: the bolster vortex at the windward face, the lee vortex at the leeward face, and the separated wake region (figure reproduced based on Oke [4]).

The aspect ratio of the canyon is defined as the ratio of the building height (H) and the canyon width (W), $AR = H/W$. For canyons with low aspect ratios ($AR < 0.05$), a scenario wherein the buildings are far apart, the flow fields around the buildings do not interact: the flow separating from the upstream building reattaches within the canyon, forming a new boundary layer. Hence a bolster vortex is formed upstream of the downwind building as if the latter was in isolation. Oke [4] defines three different flow regimes within the Urban Canyon based on the aspect ratio (see figure 2) where the oncoming flow is perpendicular to the street canyons.

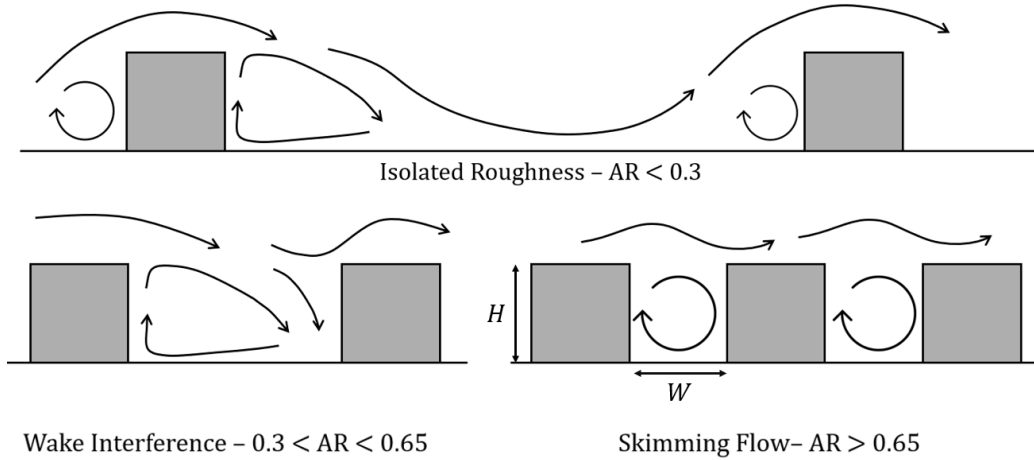


Figure 2: Schematic of flow regimes within an urban street canyon as described by Oke [4]

For canyons with aspect ratios $0.05 < AR < 0.3$, the wakes of the buildings begin to interact. However, the lee vortex of the upstream building does not interact with the bolster vortex of the downstream building. This regime is called the isolated roughness flow. In canyons with aspect ratios $0.3 < AR < 0.65$, the lee vortex of the upstream building begins to interact with the bolster vortex of the downstream building. This regime is called the wake-interference flow. In this regime, mixing within the canyon is enhanced by the interaction of all three zones (lee vortex, bolster vortex, and the wake) of the flow field around the building. When the aspect ratio $AR > 0.65$, a spanwise vortex is formed within the canyon. This regime is called the skimming flow regime. In this regime, the buildings have a 'sheltering effect'

wherein the bulk of the mean flow above the roof level does not enter the canyon. This represents the worst-case scenario for street canyon ventilation, leading to high pollutant concentrations at pedestrian level (Li et al. [5]). Apart from the aspect ratio, the transition between the three regimes is also dependent on the L/W ratio of the canyon (as reported by Oke [4]). Following from the above discussion, the case of the skimming flow regime of the urban street canyon is examined in this work. For canyons with $L/W > 7$ and incoming wind perpendicular to the canyon axis, the flow at the center of the canyon is reported to be 2D in its bulk, free from the 3D effects at the ends of the canyon (Hunter et al. [6]).

The building height-based Reynolds number, $Re = U_{ref}H/\nu$ is an important parameter to satisfy flow similarity between the full-scale buildings and the scaled model, where U_{ref} is the reference velocity, herein defined as the velocity at height $2H$ from the roof level at the edge of the canyon and ν is the kinematic viscosity of the fluid. In wind tunnel experiments, the building height is of the order $0.01 - 0.1$ m compared to full-scale field measurements with buildings of the order of 10m. The corresponding Reynolds numbers between the wind tunnel experiments and the field studies have a difference of 2 orders of magnitude (Chew et al. [2]). This mismatch of Reynolds numbers poses the question of whether the wind tunnel measurements with scaled models are representative of the flow over full-scale buildings. If the geometry of the urban street canyon features predominantly sharp edges, the urban street canyon exhibits little dependency on the Reynolds number for $Re > Re_{crit}$, where Re_{crit} is the critical Reynolds number (Stathopoulos and Baniotopoulos [7]). Chew et al. [2] performed water channel experiments using Acoustic Doppler Velocimetry (ADV) to measure three velocity components along a vertical profile at the center plane of the canyon. They state that a generally acceptable critical Reynolds number for mean velocities is $Re_c \approx 12000$ for Urban Street Canyons with $AR=1$. More recent studies by Cui et al. [8] recommend a critical Reynolds of $Re_{crit} = 33000$. For canyons with $AR=1$, only a single spanwise vortex is observed for all Reynolds numbers tested, ranging from reduced-scale tests at $Re = 1000$ up to full-scale field studies at $Re = 10^5 - 10^6$ (Caton et al. [9], Kovar-Panskus et al. [10], Meroney et al. [11]).

Several experimental studies have been performed on urban canyons using point-wise measurement techniques. Chen et al. [17] and Hang and Chen

Table 1: Summary of Urban Street Canyon studies conducted with aspect ratio unity

Study	Reynolds No. Tested	Re_{crit}	Vortex
Chew et al. [2]	19000-62000	12000	Yes, single
Kovar-Panskus et al. [10]	9500-19000		Yes, single
Meroney et al. [11]	20000		Yes, single
Caton et al. [9]	1000-3000		Yes, single
Baik et al. [12]	10000		Yes, single
Gerdes and Olivari [13]	3400-44000		Yes, single
Cui et al. [8]	1000-65000	33000	Yes, single
Kellnerová et al. [14]	40000		Yes, single
Kastner-Klein et al. [15]	56000		Yes, single
Wu et al. [16]	8000-65000	31000	Yes, single

[18] performed sonic anemometry measurements in a large-scale urban street canyon facility to study the flow behavior and urban microclimate in street canyons. Kovar-Panskus et al. [10] performed pulsed wire anemometry to study the flow field in an urban canyon in an atmospheric boundary layer wind tunnel. Gromke and Ruck [19] studied the effect of vegetation on the flow field and pollutant dispersion in a street canyon using two-component Laser Doppler Velocimetry (LDV). These studies employ pointwise measurement techniques capable of providing only limited information on the spatial structure of the flow within the canyon. Particle Image Velocimetry (PIV), meanwhile, is a versatile measurement technique capable of providing 2D and 3D flow fields inside the canyon. Takimoto et al. [20] performed a planar PIV experiment along the canyon center plane to study atmospheric turbulence over an outdoor urban scale model. Kellnerová et al. [14] analyzed coherent structures in a wind tunnel scale urban street canyon using time-resolved planar PIV. Caton et al. [9] conducted a water channel experiment at a Reynolds number of 30000 using planar PIV and LIF to study the velocity fields and dispersion mechanisms. Gerdes and Olivari [13] used planar PIV to study the mean flow fields within an urban canyon at Reynolds number of 4000. More recently, it has become possible to perform large-scale 3D PIV using Lagrangian Particle Tracking (3D-LPT) thanks to the Shake-The-Box algorithm (Schanz et al. [21]) using Helium-filled Soap Bubbles (Scarano et al. [22]) for volumes of the order of $1m^3$. Based on the discussion above, it emerges that: 1) a detailed characterization of the three-dimensional flow topology of an urban street canyon in the skimming regime ($AR = 1$) and

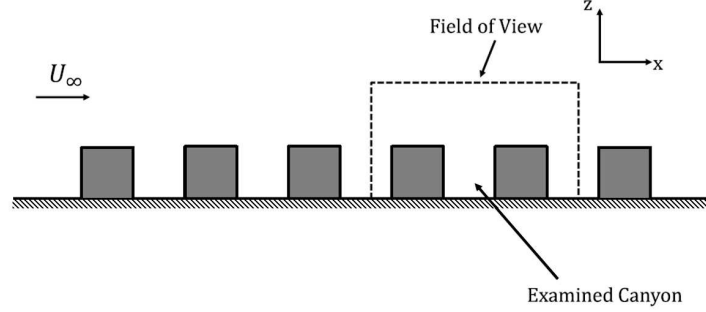
100 $L/H = 8$ at different Reynolds numbers is currently missing; 2) there is no
 consensus on the value of the critical Reynolds number, especially for higher
 order statistics. Hence, in this work, we propose to characterize the urban
 canyon flow topology by three-dimensional Lagrangian Particle Tracking and
 to investigate the Reynolds number independence of both time-average ve-
 locity components and Reynolds stresses.

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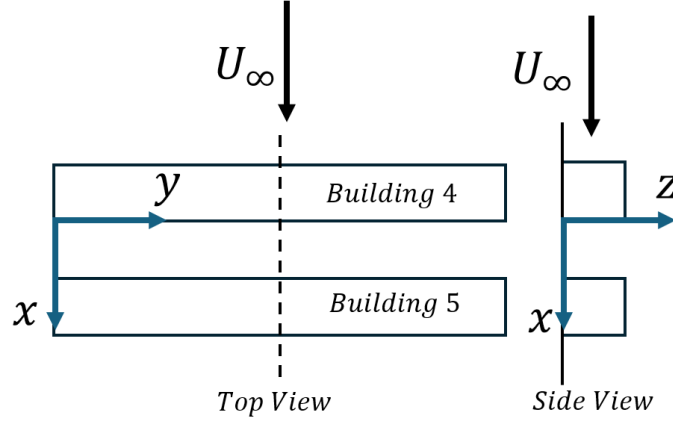
2. Experimental Setup

2.1. Wind Tunnel Setup

110 The experiment was performed in the Open Jet Facility (OJF) at Delft
 University of Technology in The Netherlands, a closed-circuit, open-jet wind
 tunnel with an outlet size of $2.85m \times 2.85m$ with a maximum speed of 30
 m/s and a nominal turbulence intensity of 1%. Six simplified building mod-
 els were mounted on a plate downstream of the outlet. The experimental
 schematic is presented in figure 3a. The buildings have a height of 50mm, a
 span of 400mm, and the canyon width is 50mm, corresponding to a canyon
 115 aspect ratio of $H/W = 1$ and $L/W = 8$. The canyon studied in the present
 experiment is between buildings 4 and 5 (figure 3a). The coordinate system
 of the canyon system is as follows: the x-axis is oriented in the streamwise
 direction, the y-axis is pointing into the canyon, and the z-axis is oriented
 vertically upwards with the origin at the base of the upstream building on
 120 the edge closer to the cameras (see figure 3b). Reynolds numbers tested
 are between 10000 and 30000 (table 3), covering the ranges of the critical
 Reynolds number (Re_{crit}) as reported in the literature (Shu et al. [23], Chew
 et al. [2]).



(a) Experimental Layout highlighting the measurement field of view



(b) Coordinate System

Figure 3: Schematic of the Experiment

2.2. Measurement System

Three-dimensional flow measurements were performed using large-scale Lagrangian Particle Tracking (LPT). The LPT setup is shown in figure 4. The setup consists of three high-speed cameras mounted in-line, with a tomographic aperture of 25° . The cameras are Photron FastCam SA1.1 with a resolution of 1MPx and a maximum acquisition frequency of 5.4kHz at full resolution (table 2). The field of view of the system is $130mm \times 270mm$ with a digital image resolution of approximately $4px/mm$ (figure 3a, 4). The acquisition frequency of the camera system is adjusted according to the freestream velocity to maintain a constant particle image displacement of about 40 pixels in the freestream. A 300W LaVision LED Flashlight 300 LED with a wavelength of $\lambda = 445nm$ is used to illuminate the region within and above

the examined canyon. Helium-filled soap bubbles (HFSB) (Scarano et al. [22]) are used as high-intensity tracer particles in the wind tunnel test section. The HFSB seeding system comprises 400 nozzles arranged in 8 parallel wings of 2m span. The seeding surface area covers $1 \times 2 \text{ m}^2$ in the settling chamber. Considering that the wind tunnel has an area contraction ratio of 3, the seeded area at the open jet outlet is $0.6 \times 1.2 \text{ m}^2$. The bubble generator supplying the seeding rake is operated by a fluid supply unit (FSU), which controls the pressures of air, helium, and soap. The nominal diameter of the tracer particles is $300 \mu\text{m}$ with a maximum expected dispersion of $50 \mu\text{m}$ (Kim et al. [24], Faleiros et al. [25]).

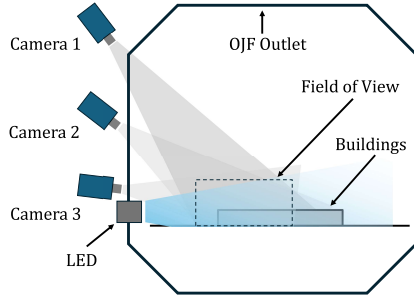


Figure 4: Illustration of the LPT Setup in the Open Jet Facility (OJF)

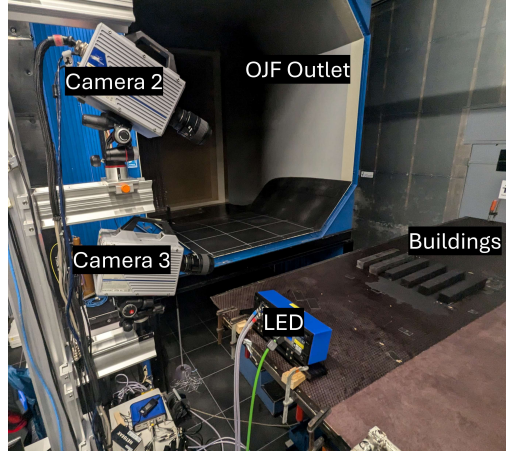


Figure 5: Experimental Setup

Table 2: Camera Details

	Camera 1	Camera 2	Camera 3
Camera Type	Photron FastCam SA1.1	Photron FastCam SA1.1	Photron FastCam SA1.1
Lens	Nikkor 210mm	Nikkor 105mm	Nikkor 105mm
f#	16	16	16

To ensure sufficient statistical convergence, data was acquired corresponding to at least 100 turnovers of the spanwise canyon vortex assuming the vortex circumferential velocity $u_{circ} \approx 0.3U_{ref}$ (Gromke and Ruck [19]) over several acquisition runs (see table 3). The raw image data was pre-processed

to remove the background intensity and reflections using a sliding minimum filter with a filter width of 7 images. Lagrangian Particle Tracking was performed using the Shake-The-Box algorithm (Schanz et al. [21]) implemented in the DaVis 10 software from LaVision GmbH. The Lagrangian Particle Tracks were then collected in Eulerian bins (Agüera et al. [26]) using a second-order polynomial regression for subsequent data processing. A bin with a side length of 64 voxels was used, corresponding to $15mm$ edge length per bin in physical space, with an overlap of 75% and a minimum of 100 particles per bin for ensemble averaging. Hence, the resulting vector spacing was $3.75mm$.

Table 3: Test Matrix

Case	Re	U_∞ [m/s]	Acq. Runs	Images/acq.	Acq. Frequency [Hz]	Vortex Turnovers
1	10000	3	1	5457	300	104
2	13000	4	1	5457	400	104
3	17000	5	3	3000	500	172
4	20000	6	3	3000	600	172
5	23000	7	1	5457	700	104
6	27000	8	1	5457	800	104
7	30000	9	1	5457	900	104

2.3. Reynolds Number Independence Criterion

To quantitatively assess Reynolds number independence, a physical quantity of interest must be considered. We define the Reynolds number independence based on the following quantity:

$$\epsilon_q = \frac{1}{\sqrt{\sum q_{i+1}^2}} \cdot \sqrt{\sum |q_i - q_{i+1}|^2} \quad (1)$$

where q is a flow quantity (mean or higher-order statistics), and the subscript i refers to the Reynolds number in ascending order. This quantity measures the relative change in the flow quantity with increasing Reynolds numbers. As the Reynolds number increases, the difference in magnitudes of flow variables (mean velocity and higher-order statistics) is expected to reduce in a converging trend. When this relative change drops below a certain threshold, the flow quantity is considered Reynolds number independent. Taking into account the measurement noise and uncertainty associated with experimental techniques ($1 - 2\%$, see section 2.4), the threshold for Reynolds

number independence was set at $\epsilon_q \leq 0.1$. A conservative value was chosen
 175 for ϵ_q to account for uncertainties associated with velocity estimation near
 the walls due to low seeding density and low illumination.

2.4. Uncertainty Quantification

This section briefly discusses the uncertainties associated with the compu-
 tation of statistical flow properties from LPT data. The standard uncertainty
 180 of the mean velocity measurements is given by (Sciacchitano and Wieneke
 [27]):

$$\mathcal{U}_{\bar{u}} = \frac{\sigma_u}{\sqrt{N_I}} \quad (2)$$

where $\mathcal{U}_{\bar{u}}$ is the uncertainty associated with the time-average velocity
 estimation, σ_u is the standard deviation of the velocity, and N_I is the number
 of independent velocity measurements per bin (number of vortex turnovers).
 185 For the Reynolds normal stresses, the standard uncertainty is computed using
 equation 3 (Sciacchitano and Wieneke [27]):

$$\mathcal{U}_{\overline{u'u'}} = \sigma_u^2 \sqrt{\frac{2}{N_I - 1}} \approx \sigma_u^2 \sqrt{\frac{2}{N_I}} = \overline{u'u'} \sqrt{\frac{2}{N_I}} \quad (3)$$

and for the Reynolds shear stress, the standard uncertainty is computed
 using equation 4 (Sciacchitano and Wieneke [27]):

$$\mathcal{U}_{\overline{u'v'}} = \sigma_u \sigma_v \cdot \sqrt{\frac{1 + \rho_{uv}^2}{N_I - 1}} \quad (4)$$

where ρ_{uv} is the cross-correlation coefficient between the errors of the two
 190 velocity components.

Figure 6 presents the relative uncertainties in time-averaged velocity and
 Reynolds Stress estimation along a vertical profile at $x/W = 0.5$, and a
 spanwise location $y/L = 0.25$. The uncertainty in velocity estimation is
 195 normalized by U_{ref} , and the uncertainty in Reynolds stress estimation is
 normalized by U_{ref}^2 . The standard uncertainty in mean velocity estimation
 is of the order of 0.5% of the reference velocity within the canyon and in-
 creases to about 1% in the shear-dominated region at the roof level and in the
 turbulent flow above the roof. The uncertainties in the measurement of the
 200 other velocity components and at other spanwise locations are of the same

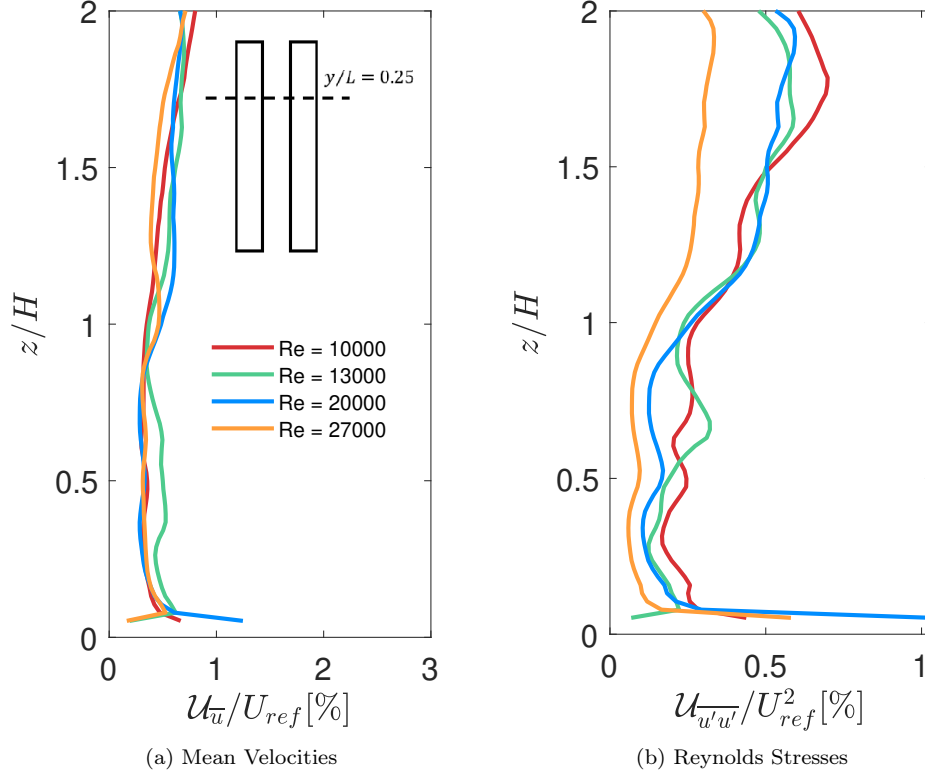


Figure 6: Relative Standard Uncertainties along a vertical profile at $x/W = 0.5$ and $y/L = 0.25$

order and, therefore, are not presented here for brevity. The uncertainty in the measurement of fluctuating quantities like the Reynolds stresses is the highest near the floor of the canyon and drops to about 0.5% of the squared reference velocity within the canyon and above.

205 3. Results and Discussion

3.1. Flow Topology

Before discussing the Reynolds number effects on the urban canyon flow, the flow topology is presented at the highest measured Reynolds number, $Re = 30000$. Figure 7 illustrates the streamwise velocity contours and in-plane vectors at three spanwise locations. The velocity vectors highlight the presence of a spanwise vortex within the canyon, driven by flow above the

roof of the buildings. The x-position of the center of the vortex, identified by the maximum of the Γ_1 criterion (Graftieaux et al. [28]), moves from the leeward side near the edge of the canyon to the windward side near the center plane of the canyon. Figures 8 and 9 highlight this further. In particular, it is at $x/W = 0.25$ at the outer edge of the canyon, while it moves downstream when approaching the mid-span of the canyon, reaching $x/W = 0.7$ at the mid-span.

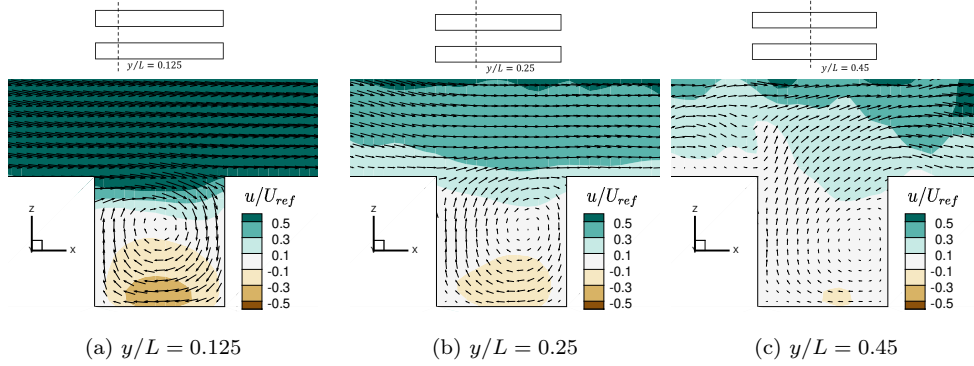


Figure 7: Streamwise velocity contours and vectors at three span-wise locations

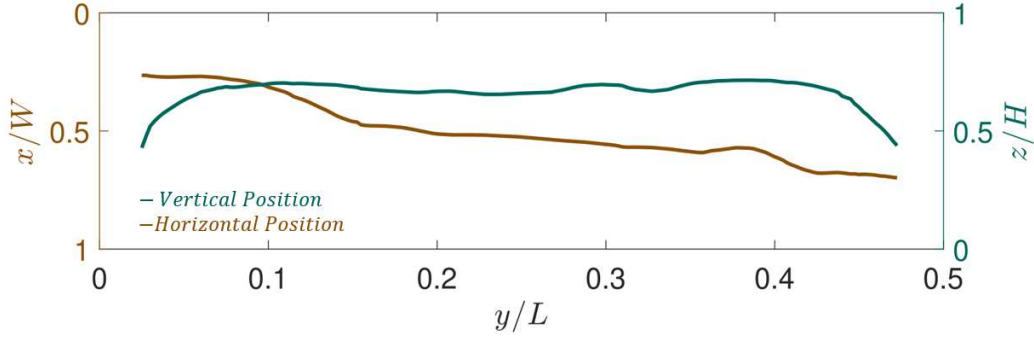


Figure 8: Position of the canyon vortex center along the canyon span

Aside from the spanwise vortex, it is noticed that the entrainment of air from the edge of the canyon creates a vertically oriented flow structure, henceforth called the end vortex, as can be seen by the vectors in figure 9.

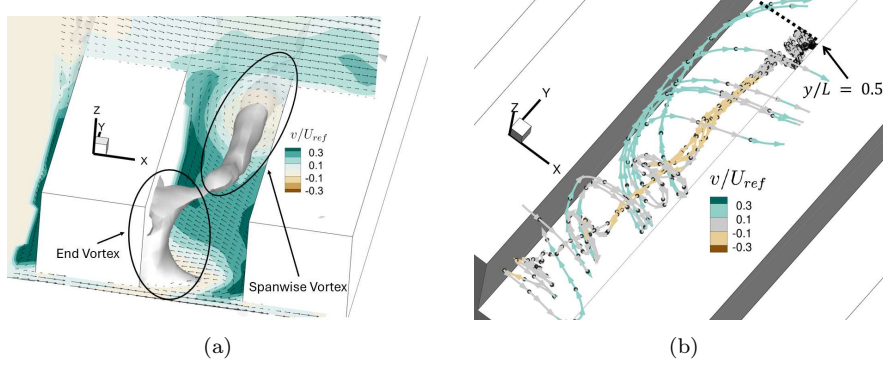


Figure 9: 3D Flow Topology of the Urban Street Canyon. (a) Lateral velocity iso-surface $v/U_{ref} = -0.1$ highlights the presence of the spanwise vortex and the end vortex. Lateral velocity contours indicate spanwise motion of the flow within the canyon. The vectors plotted are tangent to the contour planes. The vertical plane is plotted at $y/L = 0.25$, and the horizontal plane is plotted at $z/H = 0.05$ (b) Streamlines showing the flow path within the canyon vortex system.

Figure 9 presents the three-dimensional flow topology within the urban street canyon. In figure 9a, an iso-surface corresponding to the lateral velocity $v/U_{ref} = -0.1$ is plotted to highlight the interaction between the end vortex and the spanwise vortex. An iso-surface of the lateral velocity was chosen here to highlight the large-scale vortical structures, as traditional derivative-based vortex identification criteria, such as the Q-criterion, were noisy and reduced clarity for visualization purposes. The end vortex, oriented vertically, enhances the entrainment of air into the canyon from the sides. The flow induced by the end vortex pushes the spanwise vortex further upstream in the regions near the end of the canyon. The effect of the end canyon vortex reduces going towards the center plane of the canyon and, subsequently, the canyon vortex is primarily driven by the shear flow at the roof level, pushing the vortex core towards the windward face of the canyon thereby producing the curved vortex structure over the semi-span of the canyon as observed in figure 9 and figure 8. Figure 9b shows streamtracers within the canyon, with the arrows indicating the flow direction. It can be observed that at the core of the canyon vortex, there is a spanwise flow away from the center plane. This is explained by the fact that the circulation is the strongest closer to the end of the canyon, around $y/L = 0.1$, and, therefore, the pressure at this location is at its minimum. This low-pressure region drives the canyon vortex core flow away from the center plane. The canyon vortex core flow then interacts with the entrained flow from the canyon edge and roof, forming the canyon

vortex, and eventually exiting the canyon near the center plane.

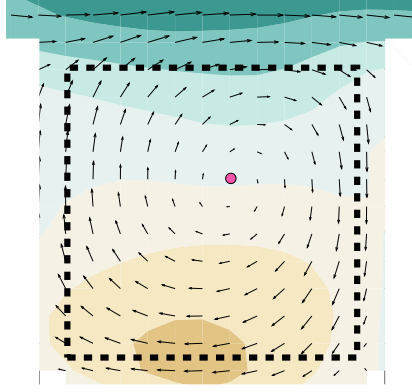


Figure 10: Dashed Line - The closed curve used for computing circulation within the canyon. Red Dot - Vortex Center computed using the Γ_1 criterion.

245 3.2. Flow Topology at the center plane $y/L = 0.5$

It was observed in the previous section that the size and strength of the canyon vortex reduces as y/L approaches 0.5 (further discussion on the canyon vortex strength in the following section). This is in contrast to the flow topology of an urban street canyon commonly reported in the literature (Hunter et al. [6]). The present study was conducted in an open-jet wind tunnel, whereas several of the experimental studies reported in the literature have been performed in closed test-section wind tunnels. It is therefore hypothesized that the differences in flow topology seen in the present study are the consequence of the open-test section.

255 To test this hypothesis, a secondary study was conducted in a smaller open-jet wind tunnel at the Delft University of Technology, with the setup modified to also allow for a closed test-section add-on. Additionally, it was possible to introduce a pressure gradient across the fetch of the buildings to investigate pressure gradient effects. Planar 2D2C PIV was employed to simplify the setup, and data was acquired at $Re = 30000$ at $y/L = 0.5$. Four cases were examined: (1) open test section, (2) closed test section, (3) closed test section with an imposed Adverse Pressure Gradient (APG), and (4) closed test section with an imposed Favourable Pressure Gradient (FPG).

265 A more detailed description of the experimental setup and PIV parameters is provided in Appendix A. The results are presented below.

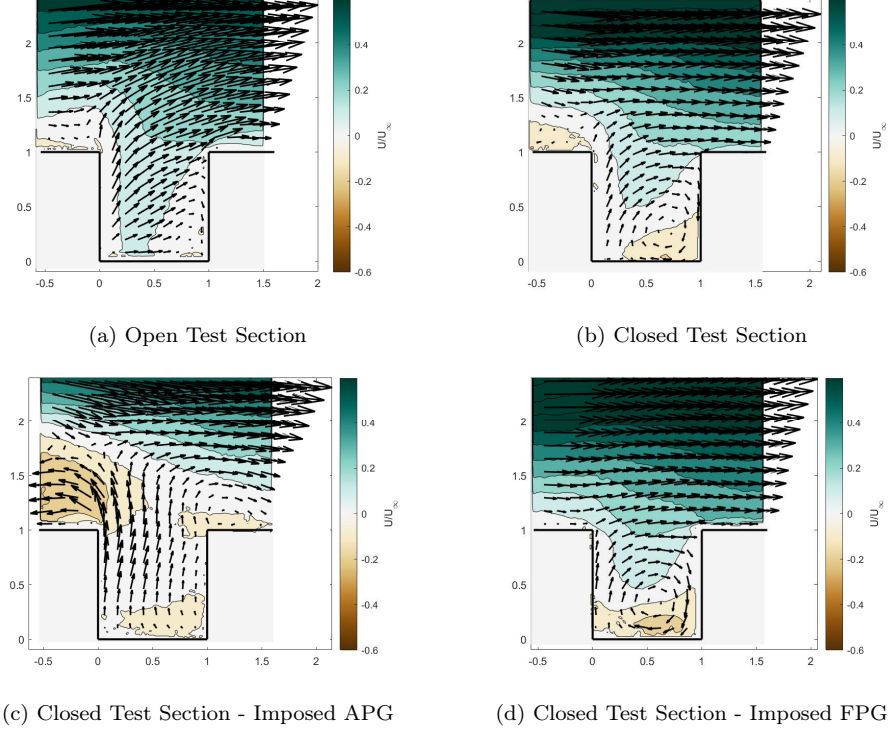


Figure 11: Normalized Streamwise Velocity contours at $y/L = 0.25$

Figure 11 presents the normalized velocity contours at $y/L = 0.5$ and $Re = 30000$. It can be observed that in the open test section case (fig 11a) and the APG case (fig 11c), the canyon vortex is absent, and in the closed test section case (fig 11b) and the FPG case (fig 11d), the canyon vortex is present. Considering the velocity contours from this 2D PIV study and keeping in mind the 3D flow topology from the main study, there seem to be two competing features in the Urban Street Canyon system. First, there is the flow entrained from the ends of the canyon, introducing a spanwise velocity that tends to push entrained air towards the center plane and then upwards and outwards. Secondly, the flow above the roof that is driving the spanwise canyon vortex. The relative strengths of these two features have an influence on whether there is a vortex or not.

280 In the case of the closed test section and the FPG case, there is an acceleration of the flow above the canyon, and this stronger flow above the roof drives the canyon vortex and is more significant compared to the flow entrained from the ends of the canyon. Conversely, in the open test section and the APG case, the flow above the roof is decelerated and is not strong
285 enough to drive the canyon vortex. The flow entrained from the ends of the canyon is more significant in this case, and we see an ejection of flow outward from the center plane of the canyon.

This correlation between the flow above the roof and the strength of the
290 canyon vortex is clear in figure 12. In cases where the mean streamwise velocity above the canyon is low, the circulation strength is also low, quantitatively confirming the absence of a canyon vortex. In cases with higher mean streamwise velocity above the canyon, the circulation strength is high, confirming the presence of the canyon vortex. Therefore, because of the absence
295 of a closed test section, the flow above the roof is free to expand, thereby lowering mean velocities. The lower velocity only weakly drives the canyon vortex and the flow entrainment from the ends of the canyon is the predominant feature, primarily causing ejection of flow from the canyon around the center plane.

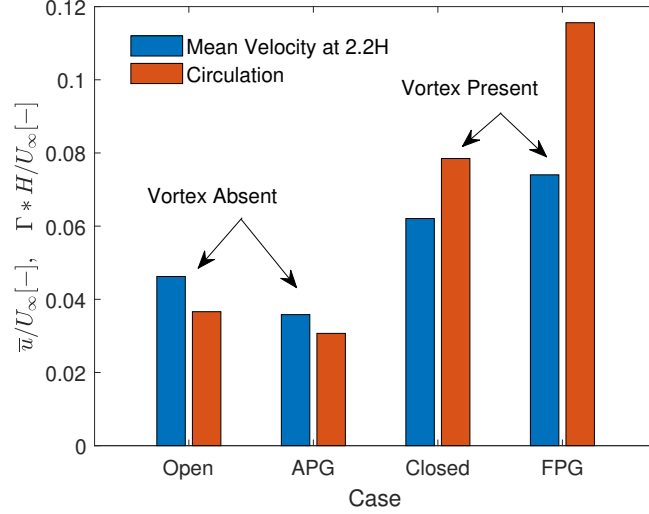


Figure 12: Circulation within the canyon and mean velocity across the canyon at $z/H = 2.2$. The mean velocity was obtained by averaging the velocity between $-0.5 \leq x/W \leq 1.5$ and $z/H = 2.2$.

3.3. Strength of the Canyon Vortex

The strength of the canyon vortex at several span-wise locations is quantified using the circulation within the canyon, computed by integrating velocity over the closed curve presented in figure 10. This curve was chosen such that the vortex is contained within the curve at all spanwise locations while also ensuring sufficient clearance from the wall, with a side length of $0.9H$ centered at the geometric center of the canyon slice. Figure 13 shows the circulation over the canyon span. The circulation reaches a maximum at around $y/L = 0.15$ because the (reverse) streamwise velocity near the floor of the canyon has a strong contribution from the end vortex, along with the contribution of the canyon vortex. The circulation reduces in strength moving towards the center plane as the effect of the end vortex weakens, and the vortex is driven primarily by the flow above the roof. Close to the center plane, the vortex disappears completely (see figure 7c) when the spanwise vortices from opposite ends of the canyon meet and eject the flow upwards and above the canyon. This is ascribed to the fact that, due to the open test section of the wind tunnel, a slight adverse pressure gradient is present above the canyon at the mid-span because of the expansion of the open jet. As a result, the streamwise velocity on the canyon roof is reduced and is

unable to feed the vorticity of the spanwise vortex at the mid-span location.
 320 This observation is in contrast with the typical flow topology of long urban
 street canyons ($L/H > 7$) commonly reported in the literature (for exam-
 ple, Li et al. [29]). The experiments reported in the literature were largely
 conducted in closed test-section wind tunnels or water channels (Chew et al.
 [2], Kovar-Panskus et al. [10], Meroney et al. [11], Baik et al. [12]), whereas
 325 the present experiment was conducted in an open-jet wind tunnel.

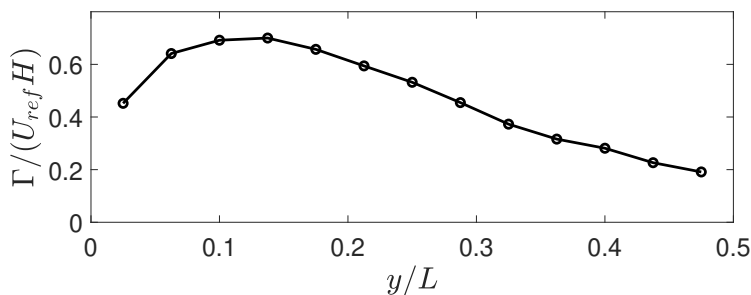


Figure 13: Circulation over the span of the canyon at $Re = 30000$

Figures 14 and 15 show spanwise slices of streamwise and vertical velocity contours, u and w respectively, at $x/W = 0.5$. These figures highlight the mechanism of ventilation within the canyon. Entrainment of fresh air happens largely at the ends of the canyon, with air entrained both from the
 330 sides as well as from above the roof level. The end vortex induces a velocity along the span of the canyon from both ends, meeting at the center plane. The entrainment of fresh air from the sides is also enhanced by the low-pressure region formed at the center of the spanwise vortex, particularly at $y/L \approx 0.15$, inducing a velocity along the canyon span. At the center of the
 335 canyon, air entrained from both ends of the canyon is then pushed upwards and out of the canyon. This happens because the streamwise velocity above the center plane of the canyon is much lower (of the order of $0.2 - 0.4U_\infty$), and this lower velocity is not sufficient to drive the canyon vortex. Therefore, air is primarily ejected from the canyon near the center plane, pushed out
 340 by the colliding air masses entrained from the ends of the canyon. This is different from the description by Hunter et al. [6], according to which the effect of the end vortices in transporting air in spanwise direction towards the canyon center is limited to $y/H = 3.5$. The following section discusses this further.

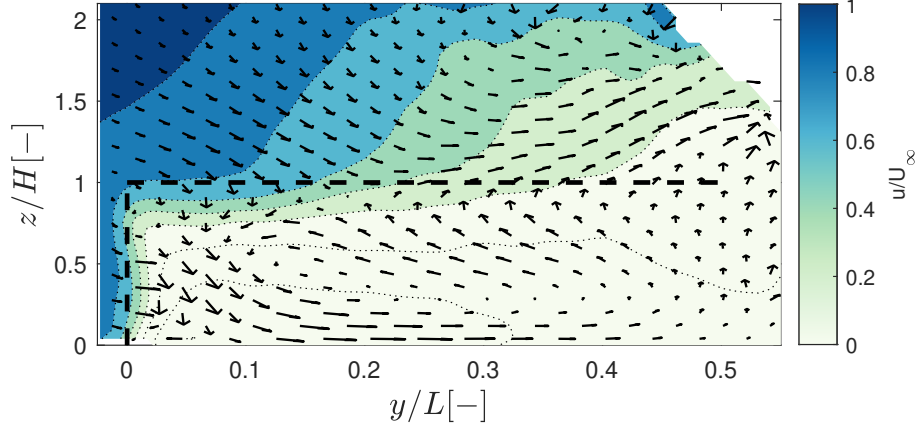


Figure 14: Streamwise velocity contours and in-plane vectors at the vertical slice along the span at $x/W = 0.5$

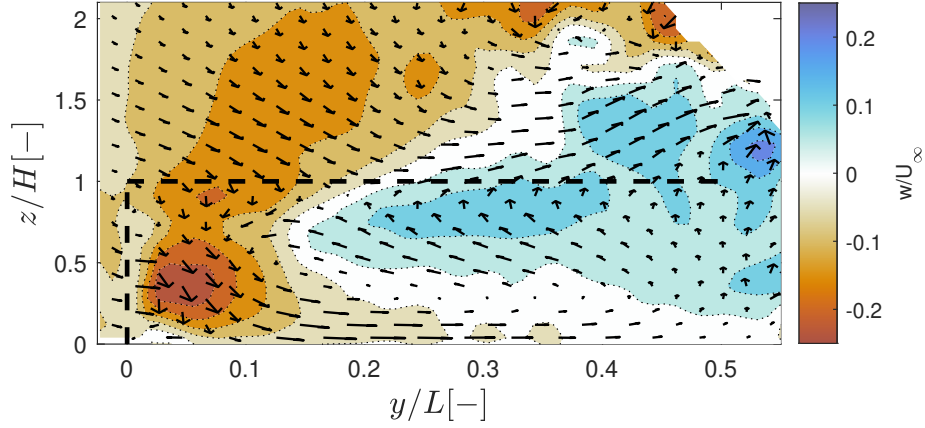


Figure 15: Vertical velocity contours and in-plane vectors at the vertical slice along the span at $x/W = 0.5$

345 3.4. Reynolds Stresses

The Reynolds normal stress $\overline{u'u'}$ is plotted in figure 16 at three span-wise locations. At $y/L = 0.125$, a peak is observed in $\overline{u'u'}$ in the upper part of the street canyon, $0.8 \leq z/H \leq 1$, due to the unsteady shear layer formed between the above-roof flow and the flow within the canyon. At this

spanwise location, because of the spanwise and vertical flow induced by the vortex structures within the canyon (see figure 15), flow hardly affected by the upstream fetch of the canyons is pulled into the canyon system. Low magnitudes of Reynolds stresses (figures 16a and 17a) above roof level (compared to corresponding values closer to the mid-span of the canyon) highlight this effect. The magnitude of $\overline{u'u'}$ is lower for $y/L = 0.25$ and $y/L = 0.45$ at the roof level ($0.8 \leq z/H \leq 1$) due to the formation of a boundary layer above the roof due to the upstream buildings. With the lower velocities within this boundary layer (see figure 7), there is a smaller magnitude of shear and therefore, a lower magnitude of Reynolds normal stress at roof level.

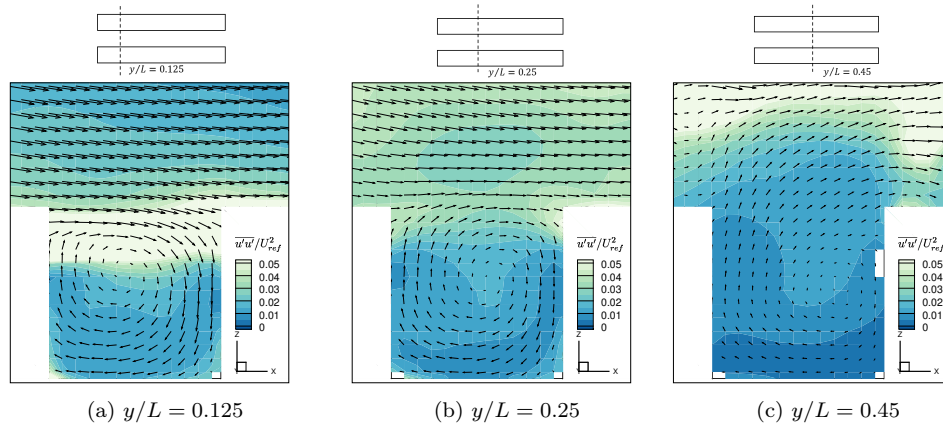


Figure 16: Reynolds normal stress $\overline{u'u'}$ contours and vectors at three span-wise locations

Figure 17 presents the Reynolds shear stress $\overline{u'w'}$ at three span-wise locations. A negative peak is observed at roof height at $y/L = 0.125$ due to instabilities in the flow caused by the strong shear transferring momentum into the canyon, followed by a strong positive peak. The positive peak in normalized Reynolds shear stress is caused by the flow impinging on the windward wall. This effect is the largest near the ends of the canyon, where the flow above the roof is less affected by the rooftop boundary layer compared to the flow closer to the center plane of the canyon. Moving closer to the canyon mid-span, the Reynolds shear stress increases above the canyon, due to the large velocity fluctuations in this region caused by the upstream buildings. Instead, the $\overline{u'w'}$ values inside the canyon decrease with respect to the end locations.

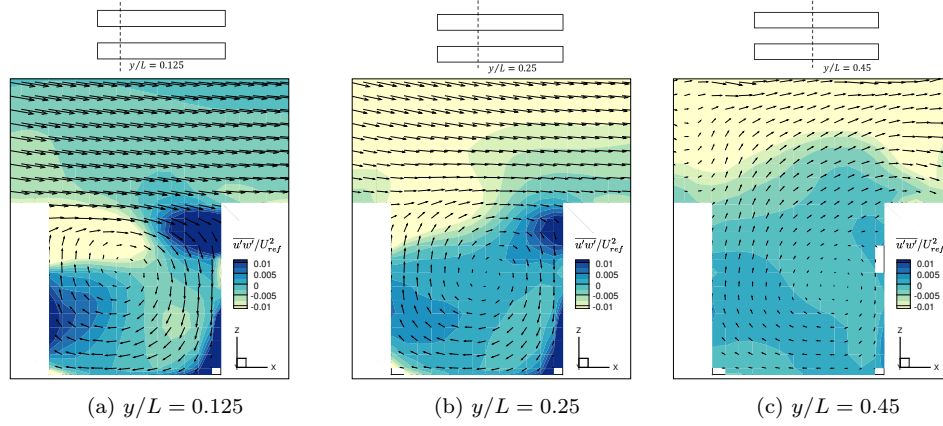


Figure 17: Reynolds shear stress $\overline{u'w'}$ contours and vectors at three span-wise locations

3.5. Reynolds Number Effects

The following section analyzes Reynolds number effects in the urban street canyon for mean velocities, circulation, and Reynolds stresses for the range of Reynolds numbers tested (see table 3). All results are presented at spanwise location $y/L = 0.25$, because the canyon vortex is clearly identifiable, and the velocity magnitudes are high enough relative to uncertainties in velocity and Reynolds stress estimation to perform a Reynolds number convergence analysis. For planes closer to $y/L = 0.5$, differences in normalized velocities at different Reynolds numbers are of the order of uncertainties in velocity estimation.

3.5.1. Time-averaged Flow Properties

Before we can determine the critical Reynolds number for higher-order statistics, we will first assess whether the critical Reynolds number for mean velocities corresponds to the values reported in the body of literature, $Re_c = 10000 - 12000$.

Streamwise velocity contours are presented in figure 18 at $y/L = 0.25$ along with in-plane velocity vectors. The overall structure of the flow within the canyon remains basically unchanged across all Reynolds numbers; however, the magnitude of the maximum normalized reverse velocity, which occurs near the canyon floor, exhibits a slight increasing trend with increasing Reynolds number (see figure 20a). The center of the vortex remains invariant as the Reynolds number increases.

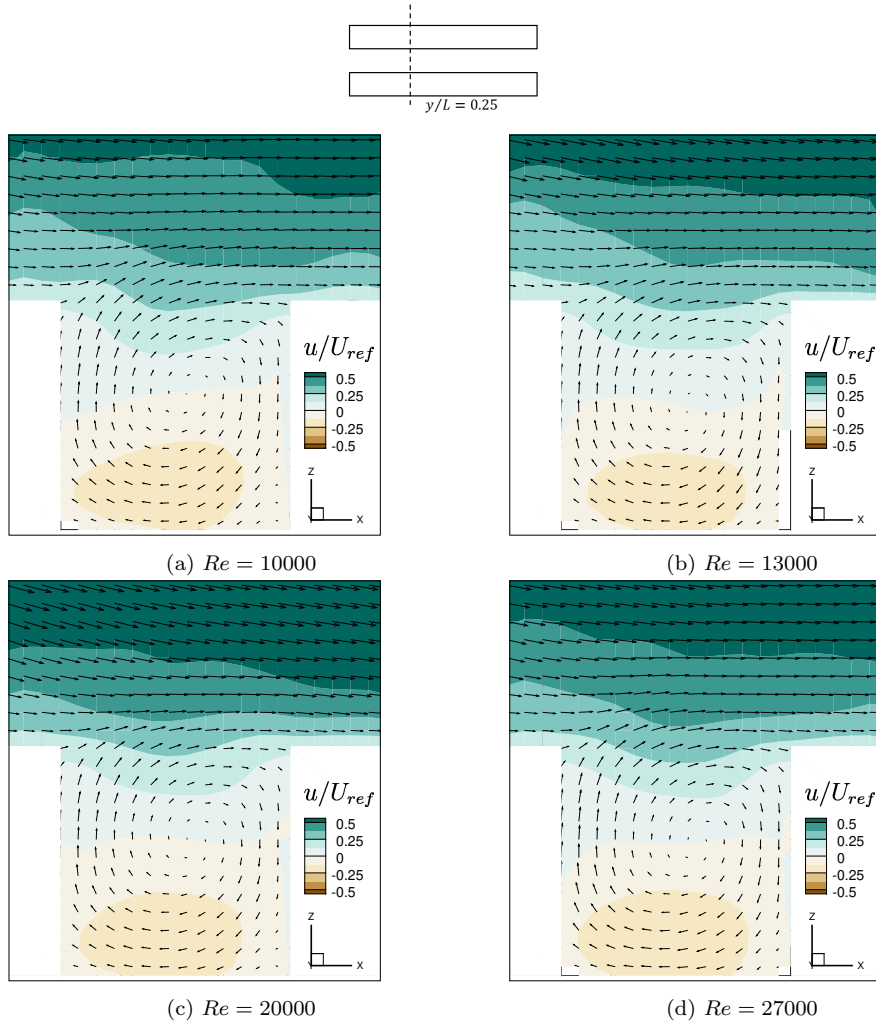


Figure 18: Normalized Streamwise Velocity contours at $y/L = 0.25$

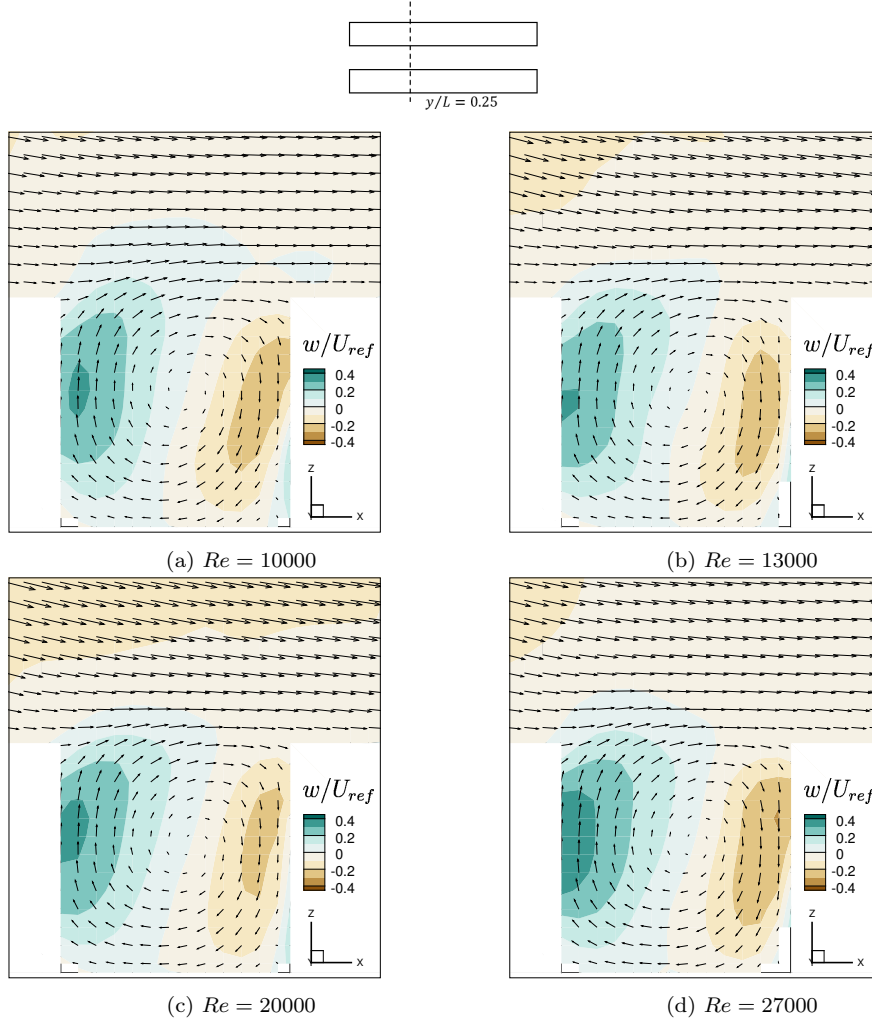


Figure 19: Velocity w contours at $y/L = 0.25$

395 Figure 19 presents the contours of normalized vertical velocity at the
spanwise location $y/L = 0.25$. Overall, the flow topology remains unchanged
for increasing Reynolds number. However, the extent of the most negative
and positive velocity regions, near the windward and leeward walls, respec-
tively, increases with increasing Reynolds number, suggesting that vertical
400 velocity is Reynolds number dependent.

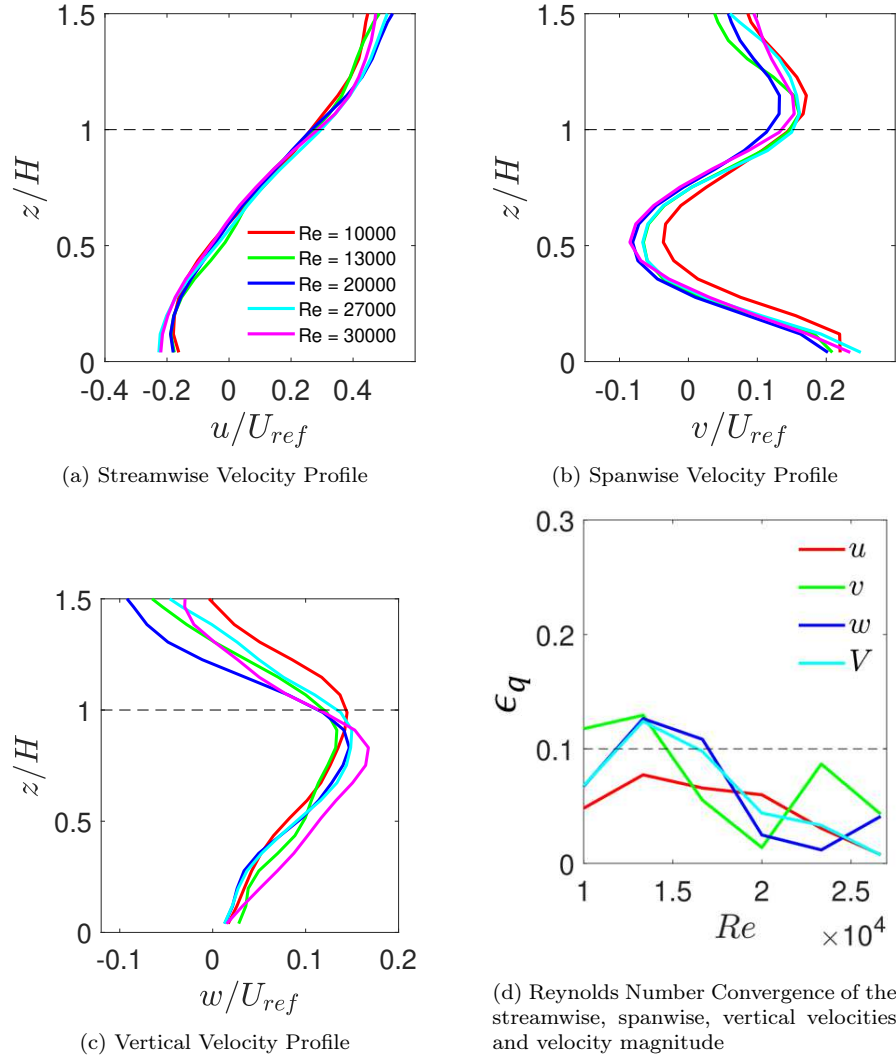


Figure 20: Mean velocities along a vertical profile at $x/W = 0.5$ and $y/L = 0.25$ and Reynolds Number convergence.

Velocity profiles taken along a vertical line at $x/W = 0.5$ and $y/L = 0.25$ are presented in figure 20. The streamwise velocity profiles (figure 20a) collapse on top of each other within the canyon away from the floor ($0.4 < z/H < 1$), indicating that the flow field is Reynolds number independent in this region. In the lower part of the canyon ($z/H \leq 0.4$), it can be observed that the streamwise velocity in the reverse flow region increases with increasing Reynolds number. However, a converging trend is observed

at higher Reynolds numbers. The spanwise velocities (figure 20b) for all Reynolds numbers fairly agree with each other within the canyon, except
410 at the lowest Reynolds number, $Re = 10000$. The vertical velocities (figure 20c) show a larger deviation with increasing Reynolds numbers, exhibiting no clear trend. However, the maximum deviation is below the threshold for Reynolds number independence as defined in section 2.3 above a Reynolds number of 17000.

Reynolds number independence is assessed using the convergence criterion introduced in section 2.3, and figure 20d presents the convergence for mean velocities averaged over the profile within the canyon, i.e. $0.2 \leq z/H \leq 0.8$. This region was chosen because below $z/H < 0.2$ the data quality was low because of reflections and low illumination intensity, and above $z/H > 0.8$ the
420 flow above the roof was directly interacting with the flow inside the canyon, making this region sensitive to disturbances in the free stream. Streamwise velocities are already Reynolds number independent within the canyon at $Re = 10000$. This was already evident from the contour plots in figure 18 and the profiles 20a. The value of the convergence criterion for the spanwise
425 velocity component and the velocity magnitude is below the threshold of $\epsilon_q = 0.1$ for Reynolds numbers above 17000 and for the vertical velocity component for Reynolds numbers above $Re = 20000$. ϵ_q decreases overall with increasing Reynolds numbers, except for the spanwise velocity.

3.5.2. Circulation

This section discusses the Reynolds number independence of the circulation strength within the urban street canyon (see figure 10). Figure 21
430 presents the variation of circulation strength over the span of the canyon with Reynolds numbers.

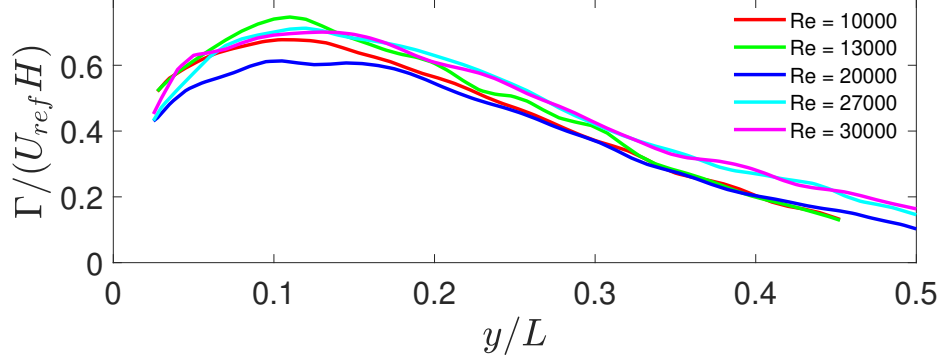


Figure 21: Circulation Strength along the canyon span

All Reynolds numbers follow a similar trend, exhibiting a peak in circula-
 435 tion strength at $y/L = 0.15$ and then decreasing towards the center plane
 of the canyon. At lower Reynolds numbers, the circulation close to the cen-
 ter plane is lower compared to higher Reynolds numbers, indicating that
 the canyon requires higher Reynolds numbers to maintain a spanwise vortex
 along the entire span. Figure 22 shows the convergence plot of the average
 440 circulation in the canyon in the region $y/L = 0.25 \pm 0.1$ as a function of
 Reynolds number. This region was chosen to study the Reynolds number in-
 dependence for other variables discussed. Additionally, because of the low
 velocity magnitudes approaching $y/L = 0.5$, the associated uncertainties are
 445 higher, further motivating the choice of $y/L = 0.25$ for the analysis. Reynolds
 number independence is achieved around $Re = 17000$ for average circulation
 within the region considered.

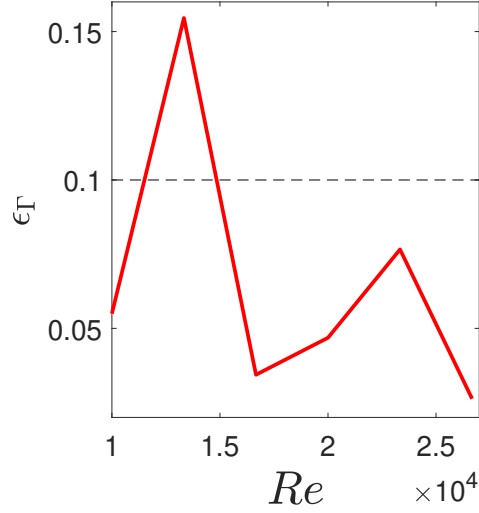


Figure 22: Convergence Plot for Circulation

3.5.3. Reynolds Stresses

This section discusses the Reynolds number independence of Reynolds
 450 Stresses $\overline{u'u'}$ and $\overline{u'w'}$ and the Turbulence Kinetic Energy (TKE) within
 the canyon. Figures 23 and 24 show the contours of normalized $\overline{u'u'}$ and
 $\overline{u'w'}$ respectively at a spanwise location of $y/L = 0.25$. In figure 23, it can
 be observed that the magnitude of normalized Reynolds stress within the
 canyon remains relatively constant with increasing Reynolds numbers, with
 455 small differences near the canyon floor. The Reynolds normal stress $\overline{u'u'}$
 peaks at roof level, which is to be expected because of the high degree of
 unsteadiness in the shear layer at roof level.

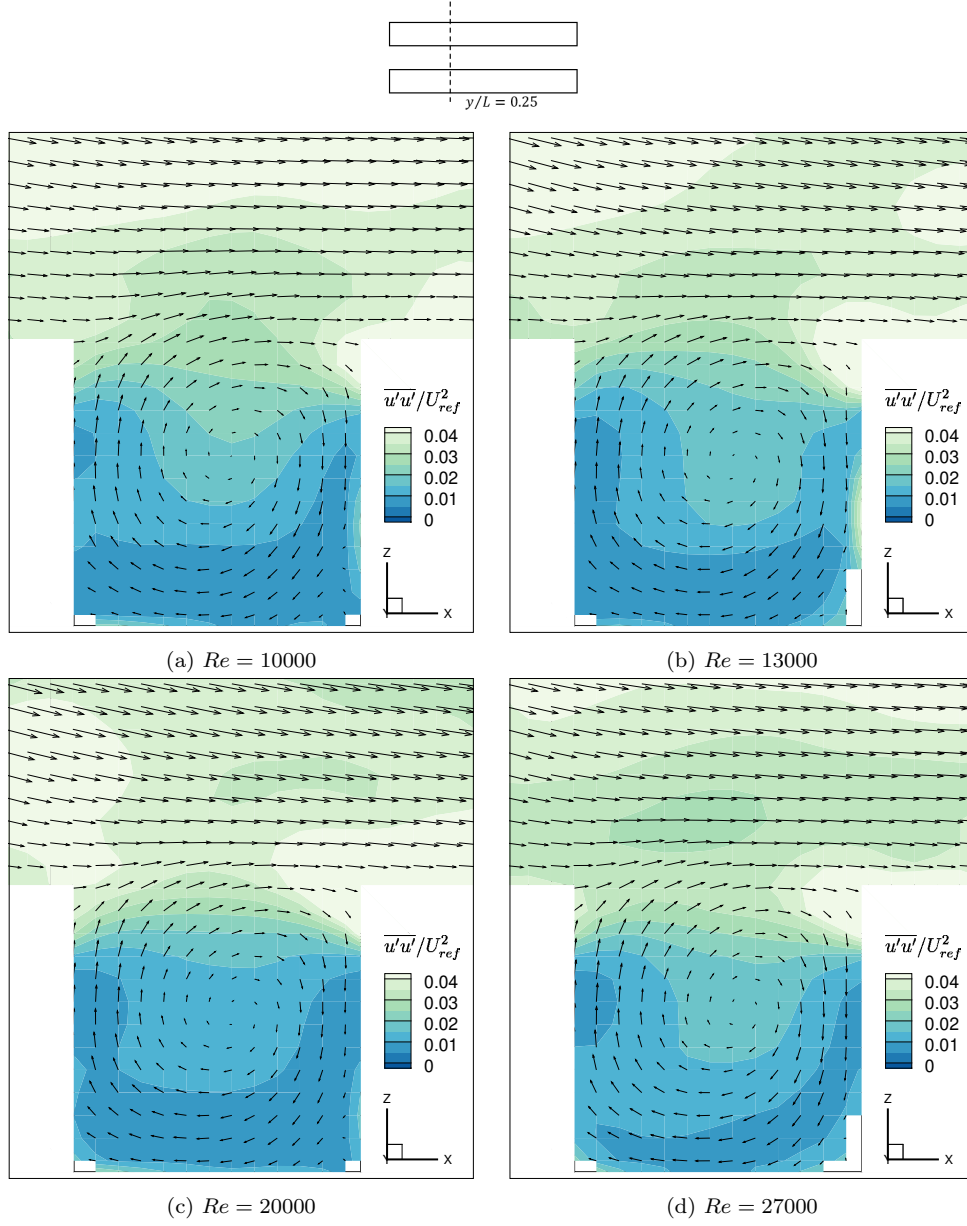


Figure 23: Reynolds Normal Stress $\overline{u'u'}$ contours at $y/L = 0.25$

A similar trend is observed in the normalized Reynolds stress $\overline{u'w'}$ as shown in figure 24 wherein small structural differences can be observed in the middle and lower regions of the canyon. The magnitude of negative $\overline{u'w'}$

460

increases with increasing Reynolds number near the roof of the leeward face of the upstream building, with the peak of positive $\overline{u'w'}$ near the roof of the windward face of the downstream building remaining relatively constant with Reynolds numbers in general, except at $Re = 13000$. However, a decreasing trend is observed on the windward face in the lower half of the canyon.

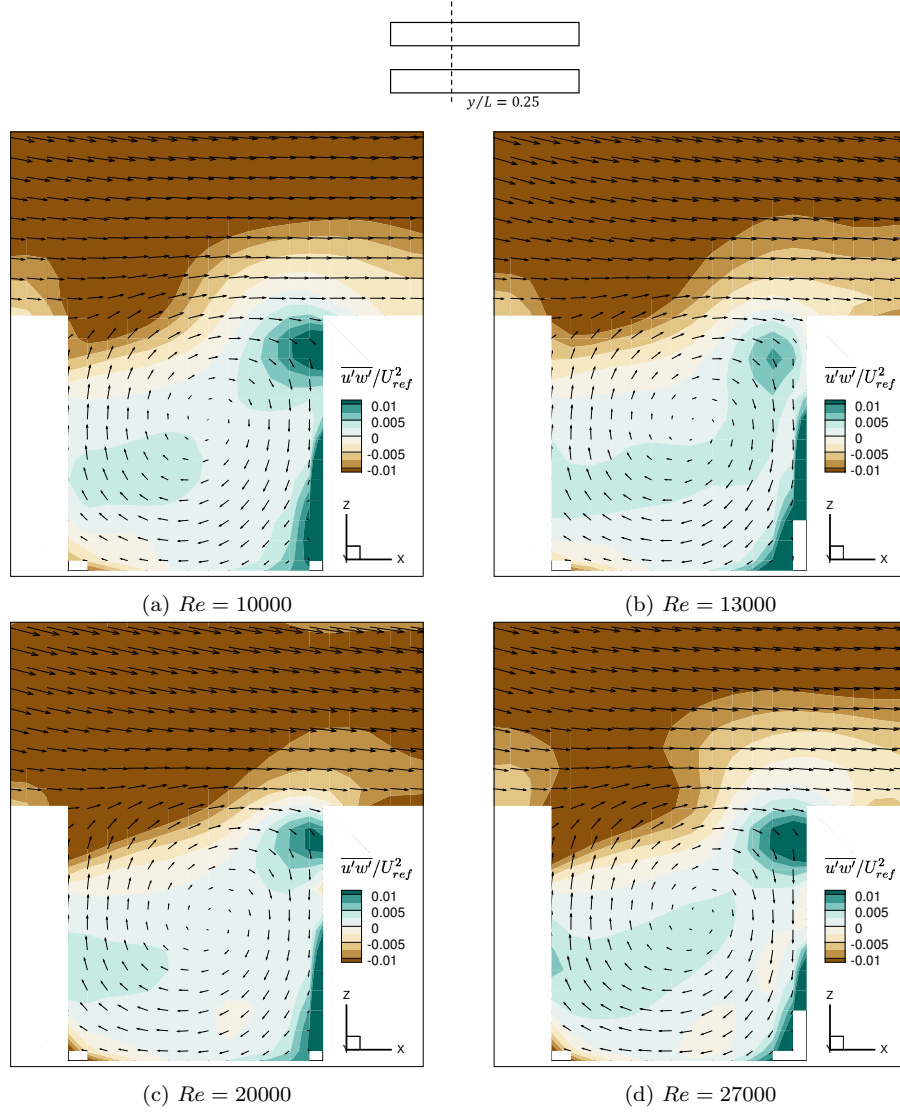


Figure 24: Reynolds Stress $\overline{u'w'}$ contours at $x/L = 0.25$

Normalized Turbulence Kinetic Energy (TKE) contours are presented in

figure 25. At all Reynolds numbers, higher TKE is observed above the canyon and a lower magnitude within the canyon. Also, within the canyon, the TKE is higher closer to the windward face of the downstream building, due to the unsteady flow entrainment from above the canyon; the TKE is the lowest close to the floor and the leeward face of the upstream building. Small differences in magnitudes are seen when increasing the Reynolds number, mainly above the canyon, with a general decrease of TKE with increasing Reynolds number.

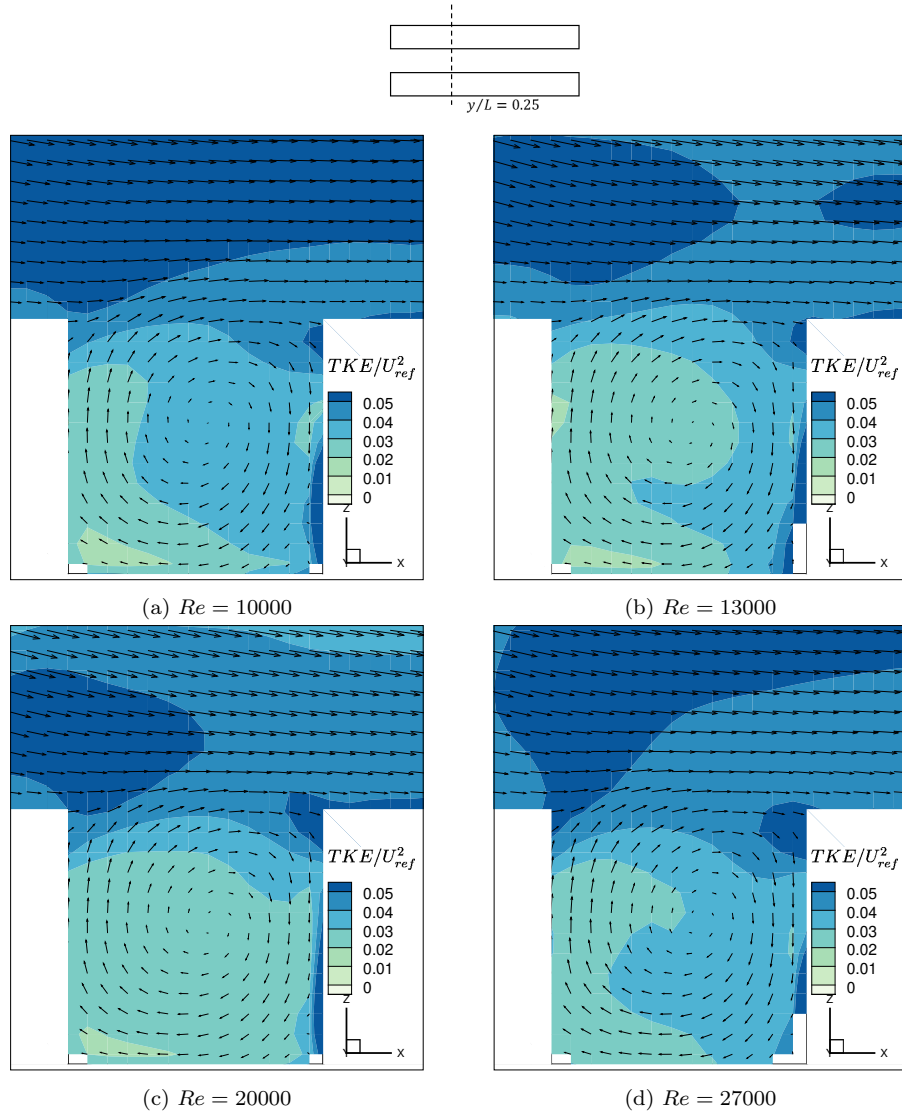


Figure 25: Turbulence Kinetic Energy contours at $x/L = 0.25$

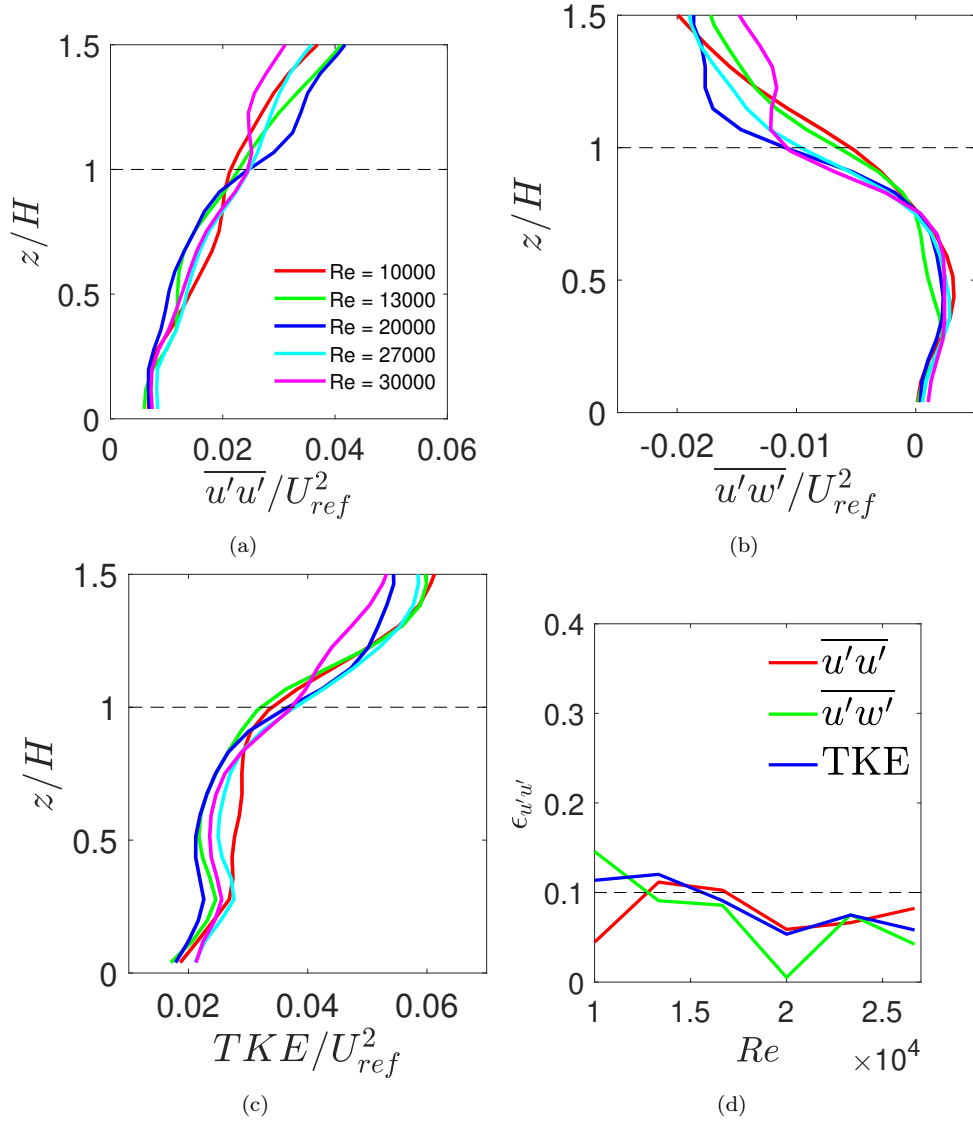


Figure 26: Reynolds Stresses, TKE, and ϵ_q along a vertical profile at $x/W = 0.5$ and $y/L = 0.25$

475 Figures 26a, 26b, and 26c present vertical profiles of normalized $\overline{u'u'}$, $\overline{u'w'}$, and TKE respectively at a spanwise location of $y/L = 0.25$ and a streamwise location of $x/W = 0.5$. The horizontal line at $z/H = 1$ indicates the roof level. The profiles of $\overline{u'u'}$ in figure 26a show, in general, an increasing trend in magnitude and scatter with increasing distance from the floor of the canyon.

480 A larger spread in the profiles is observed for different Reynolds numbers in
 the upper half of the canyon, indicating that the unsteadiness in the flow
 because of the shear layer at roof level has a degree of Reynolds number
 dependence. With the exception of the lowest Reynolds number, $Re = 10000$,
 the profiles show a converging trend within the canyon. The convergence of
 485 the Reynolds stresses is discussed in the following paragraphs. $\overline{u'w'}$ remains
 close to zero up to about $z/H = 0.7$, above which it increases in magnitude
 because of the entraining flow from above the roof level, and the curves spread
 out for different Reynolds numbers. However, close to the roof level within
 the canyon, a converging trend is observed with the profiles for $\overline{u'w'}$ collapsing
 490 on top of each other for Reynolds numbers above $Re = 20000$. Turbulence
 Kinetic Energy (figure 26c) first increases in magnitude in the lower 20% of
 the canyon and then remains relatively constant up to around 70% of the
 canyon, above which it increases further because of the unsteadiness in the
 shear layer near the roof height. This trend is observed for all Reynolds
 495 numbers within the canyon.

The convergence of Reynolds stresses and TKE to Reynolds number inde-
 pendence is presented in figure 26d based on the criterion discussed in section
 2.3. To assess convergence, the mean TKE and Reynolds stresses over the
 profile in the range $0.2 \leq z/H \leq 0.95$ are considered to minimize the er-
 500 rors associated with the division by small numbers approaching zero. The
 Reynolds stress $\overline{u'u'}$, $\overline{u'w'}$, and the turbulence kinetic energy attain Reynolds
 number independence around $Re = 17000$.

4. Conclusion

In this work, a three-dimensional flow field description is given for the
 505 urban street canyon flow using 3D Lagrangian Particle Tracking, with the
 objective to study the flow topology within the canyon and to evaluate the
 critical Reynolds number for mean velocities, Reynolds Stresses, TKE, and
 Circulation Strength in an Urban Street Canyon with $H/W = 1$ and $L/W =$
 8. Reynolds numbers ranging from $Re = 10000$ to $Re = 30000$ were tested to
 510 estimate the critical Reynolds number for the aforementioned quantities. The
 flow topology within the canyon was found to exhibit significant differences
 compared to what is reported in the literature for long canyons with $L/W >$
 7, especially concerning the existence of a canyon vortex in the center plane
 of the canyon span. There exists a vertically oriented end vortex at the
 515 edge of the canyon, which is responsible for the entrainment of air from

the sides of the canyon by inducing a spanwise velocity within the canyon. The presence of this end vortex causes the spanwise canyon vortex to have a slightly curved shape, with the vortex core located closer to the leeward face of the canyon in the regions near the edge. The vortex core gradually
520 moves towards the windward face of the canyon as it approaches the center plane of the canyon along the spanwise axis. The strength of the vortex is the highest near the ends of the canyon since the end vortex enhances flow near the canyon floor in the reverse streamwise direction. The canyon vortex reduces in strength moving closer to the mid-plane as the effect of the end
525 vortex reduces, and the canyon vortex is primarily driven by the flow over the roof. Contrary to the results presented so far in the literature, the fact that the canyon vortex is not present in the center plane is ascribed to the fact that the experiments were conducted in an open-jet wind tunnel, which resulted in a mild streamwise adverse pressure gradient over the canyon. This
530 streamwise adverse pressure gradient slows down the flow above the roof, driving the spanwise vortex less strongly, thereby favoring ejection of flow from within the canyon. Reynolds number independence was achieved for the mean streamwise velocity already at $Re = 10000$. For the spanwise velocity component and circulation, Reynolds number independence was achieved
535 at $Re = 17000$ and $Re = 20000$ for the vertical velocity component. The Reynolds number independence criterion is also met for the Reynolds stresses around $Re = 17000$. Therefore, it is recommended to use a critical Reynolds number of $Re = 20000$ for experiments involving the Urban Street Canyon with an aspect ratio of unity.

540 **Declarations**

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Authors' Contributions

545 BD - conceptualization, experiment execution, formal analysis, writing.
NPP - conceptualization, experiment execution, reviewing manuscript.
WY - conceptualization, supervision, reviewing manuscript.
DB - conceptualization, reviewing manuscript.
CG - conceptualization, reviewing manuscript.

550 AS - conceptualization, supervision, reviewing manuscript.

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Appendix A. Planar 2D2C PIV Setup

The experimental setup and PIV parameters of the planar PIV experiment (see section 3.2) are presented in this section. The planar PIV experiment was conducted to investigate the influence of a streamwise pressure gradient on the canyon vortex. This experiment was conducted in the W-tunnel, a low-speed, open-jet, open-circuit wind tunnel at the Faculty of Aerospace Engineering, TU Delft. The experimental setup is presented in figure A.27.

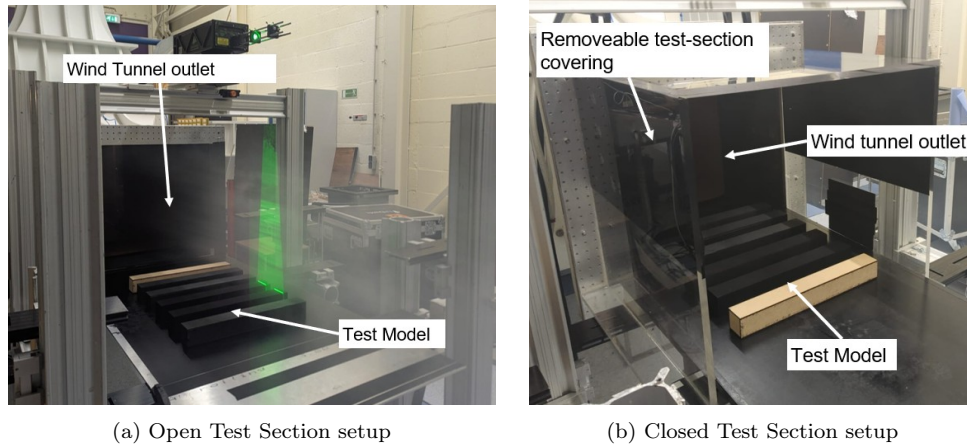


Figure A.27: Experimental setup highlighting the open jet case and the removable closed test section

565 To impose a streamwise pressure gradient over the experimental model, an enclosure was constructed around the model as shown in figure 11b. Figure A.28 presents the configurations of the enclosure to impose the required streamwise pressure gradient.

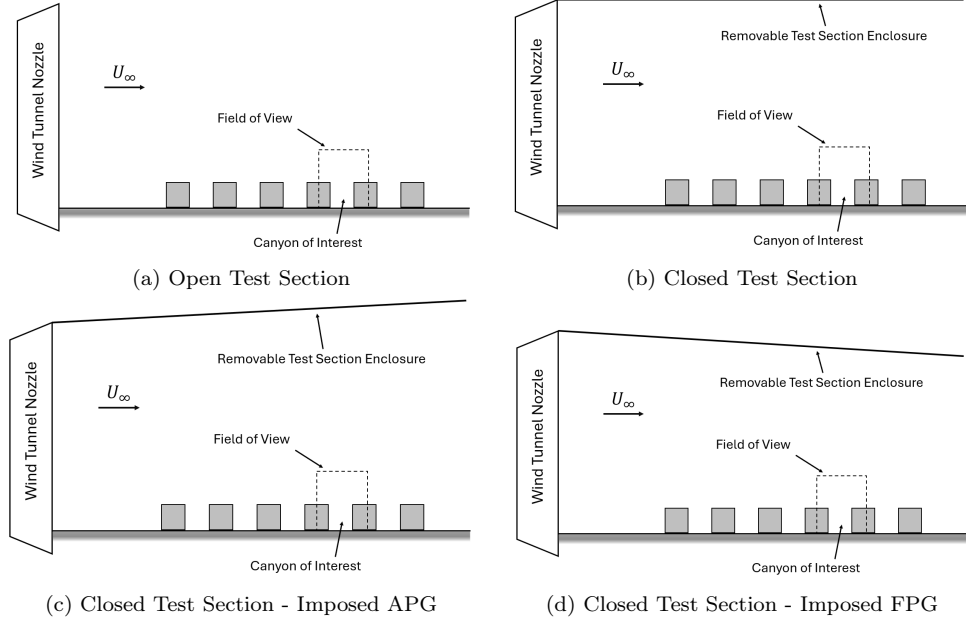


Figure A.28: Experimental Configurations to study the effect of streamwise pressure gradient on the canyon vortex

Figure A.28a is the default case of the open-jet wind tunnel and has a mild streamwise adverse pressure gradient due to the expansion of the open jet. With the addition of the closed test section (figure A.28b), the presence of the test section walls and the blockage introduced by the model induces a slight favorable pressure gradient as seen in the acceleration of flow above the models (figure 11b). In order to explicitly impose a pressure gradient, the test section enclosure is modified into a converging or diverging channel, with the angle of the channel roof w.r.t floor is $\alpha_{channel} \approx 5^\circ$ (figures A.28c and A.28d).

Planar 2D2C PIV measurements were performed at the spanwise center-plane, $y/L = 0.5$, to obtain time-averaged velocity fields. The PIV parameters are presented in table A.4

Table A.4: PIV Parameters

Freestream Velocity	9m/s
Building Height, H	50mm
Canyon Width, W	50mm
Field of View	150mm x 300mm
Lens Focal Length	50mm
Sensor Size	2560px x 2160px
Pixel Pitch	6.5 μ m
Magnification	0.11
Pulse Separation Time (dt)	65 μ s
Interrogation Window Size	32px
Interrogation Window Overlap	75%

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