

Tomo-PIV measurements in the CICLoPE Turbulent Pipe at Re_τ up to 45,000

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ABSTRACT

We report on Tomographic PIV measurements in the CICLoPE turbulent pipe facility, that is managed by the University of Bologna in Italy. Using frame-straddling and 4200 image-pairs/s, we obtain time-resolved measurements of the velocity field in a range of narrow volumes, at different distances from the wall, over the Reynolds number range Re_τ from 4,500 to 45,000. Each measurement volume is about 6 mm thick in the azimuthal direction, while the streamwise-radial extent varies, between 37×27 mm to 84×125 mm. We use smoke-particle seeding to obtain Tomo-PIV measurements, with a vector pitch of $\sim 430 \mu\text{m}$. Our focus is on the statistics and structure of the vorticity fields, which is validated against published multi-probe hot-wire results acquired in the same facility. The root-mean-square of the fluctuating components of vorticity show good agreement. For these large values of Re_τ , the pdfs of the azimuthal vorticity show a stretched exponential form. These measurements also allow us to extract the alignment of the vorticity vector with the principal directions of the rate-of-strain tensor. In addition we perform stereo-PIV measurements on two radially adjacent areas, extending in the radial direction from 0.02 to 0.65 pipe radii. This allows the study of prevalence of Uniform Momentum Zones (UMZ) and the internal intermittency.

1. Introduction

Turbulent flows in pipes or channels are of great practical importance in industry for the transport of water, gas and liquid fuel. This flow often occurs under very large Reynolds numbers, which are beyond the current computational capabilities. The ideal configuration also requires a length exceeding dozens of diameters to reach statistically steady turbulence, unaffected by the inlet conditions. The preeminent facility capable of extremely large Reynolds numbers is the Princeton superpipe (Hultmark et al., 2012), where ultrahigh pressure reduces the kinematic viscosity of the air,

to reach $Re \sim 10^7$. However, the 12-cm pipe diameter limits the experimental techniques available to study the finer details of the turbulence, and spatial resolution is a big challenge to overcome. The CICLoPE pipe facility (Talamelli et al., 2009) was constructed to address this drawback, using an order-of-magnitude larger pipe, where the latest experimental techniques (Elsinga et al., 2006; Schanz et al., 2016) can be more readily applied to resolve the broadband energy spectrum of turbulent shear flows. Using rapidly scanning laser volumes, in combination with Tomo-PIV, one can study the dynamics of the larger-scale coherent structures (Mugundhan et al., 2025).

Herein, we focus on measuring the vorticity structure in narrow laser-illuminated volumes of the flow. Earlier measurements of vorticity in this facility were carried out by Zimmerman et al. (2019), using a multi-hot-wire probe consisting of $4 \times$ –wires, which incorporates the Taylor’s hypothesis of frozen turbulence to capture all three components of the vorticity vector. However, this wire combination is not sufficient to resolve the full rate-of-strain tensor, as was done with the 20-wire probe of Tsinober et al. (1992). The vorticity statistics have been investigated in direct numerical simulations of pipe flows by Chen et al. (2020), but only up to $Re_\tau = 500$. Other notable PIV-based measurements in the CICLoPE pipe flow are the near-wall PIV measurement by Willert et al. (2017). van Doorne & Westerweel (2007) used stereoscopic PIV measurement of a transverse-section in a water pipe to visualize instantaneous vortical structures using the iso-surfaces of streamwise vorticity, employing Taylor’s hypothesis. On the other hand, in boundary-layer flows, the wall-normal variation of the root-mean-square (r.m.s) of spanwise vorticity has been measured using 4-element hot-wire probes by Klewicki (1989) and Morrill-Winter et al. (2015) up to $Re_\tau \simeq 12,700$, while all three components have been investigated from DNS at much lower $Re_\tau \lesssim 10^3$ (Lee & Sung, 2011).

2. Experimental Setup

Figure 1 shows the Tomo-PIV four-camera setup at the CICLoPE pipe facility, that is managed by the University of Bologna (Talamelli et al. (2009)). The pipe diameter is 90 cm and the inlet straight section is 110-m-long to guarantee fully-developed turbulent flow. The pressure drop is measured by a set of static pressure ports arranged periodically along the length of the pipe, thereby permitting direct estimation of the mean wall shear-stress τ_w used in evaluating the shear velocity $U_\tau = \sqrt{\tau_w/\rho}$ used in the shear Reynolds number $Re_\tau = U_\tau R/\nu$. Re_τ reaches 45,000 at the maximum centerline velocity of $U_C = 50$ m/s.

For our setup a dedicated test-section was designed and built to accommodate the optical access, with small window for the laser and a larger window for the four video cameras. A special 3-mm thick curved glass window was built by DLR and carefully aligned with the smooth pipe-wall using adjustable micrometers mounted in a metallic frame. The pipe-wall is built with the same technique used in constructing the original pipe, to guarantee the same surface smoothness.

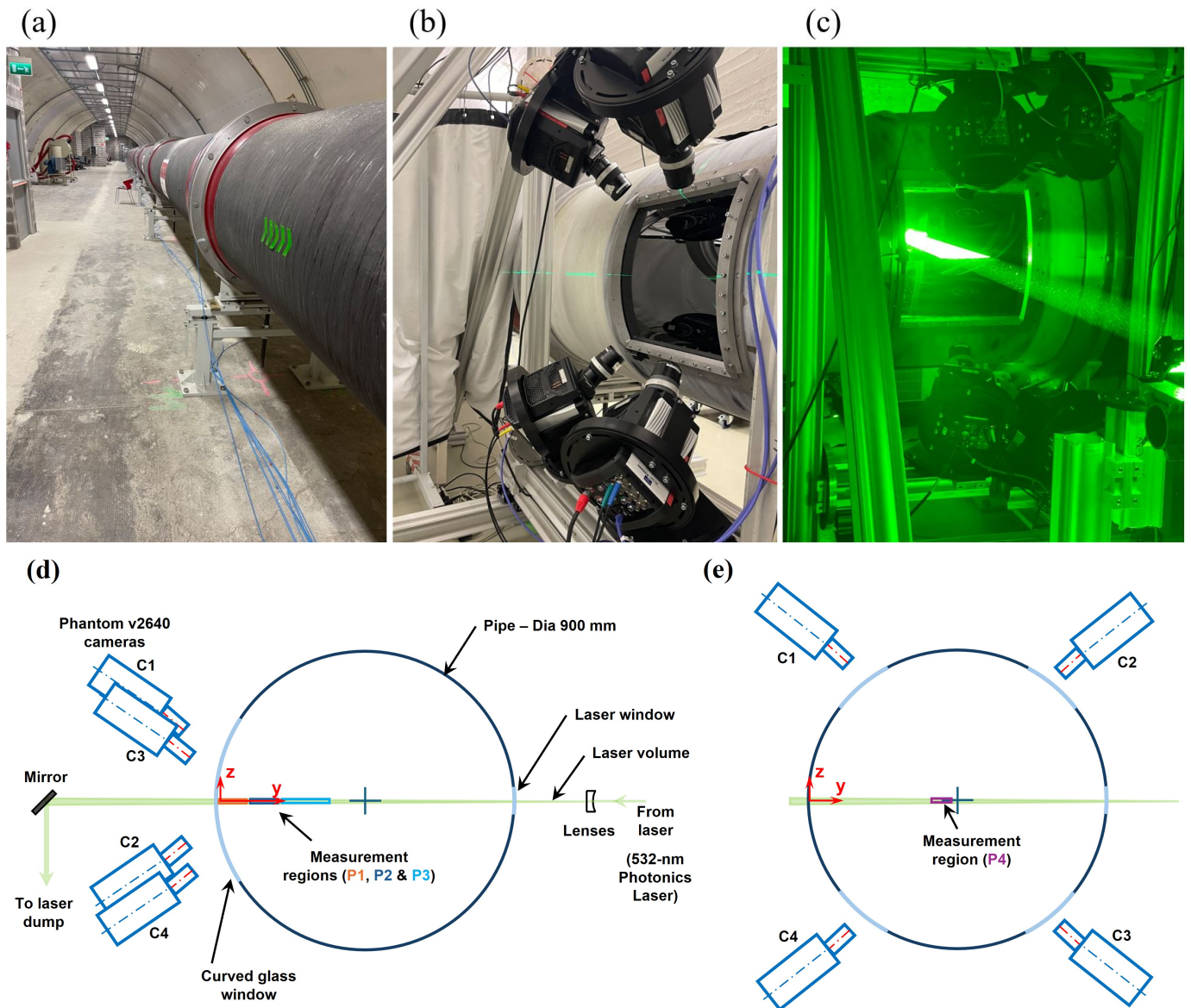


Figure 1. Experimental setup at CICLoPE pipe facility in Predappio Italy. (a) The 110 m long section of the 0.9 m-diameter pipe, with the flow in the direction of the green arrows to enter the room containing the test-section. (b) Arrangement of four high-speed video cameras used around the Tomo-PIV experimental test section, where they view the flow through a thin, curved-glass window. The lenses are on Scheimpflug mounts to improve the focus. The perpendicular alignment laser sheets are visible. (c) The laser volume illuminating the smoke particles inside the pipe. Here the cameras are aligned to acquire stereo-PIV data in two radially aligned planar segments. The laser outside the pipe is visible through airborne dust, before it is directed downwards into a beam-dump. The laser volume is 6 mm thick for the Tomo-PIV measurements, but is reduced to 3 mm for the stereo setup. The sketch in (d) shows the camera arrangement for measurement in positions **P1-P3** as well as the Stereo-PIV, while (e) shows the setup for position **P4** near the centerline. Measurements in different positions are performed on different days.

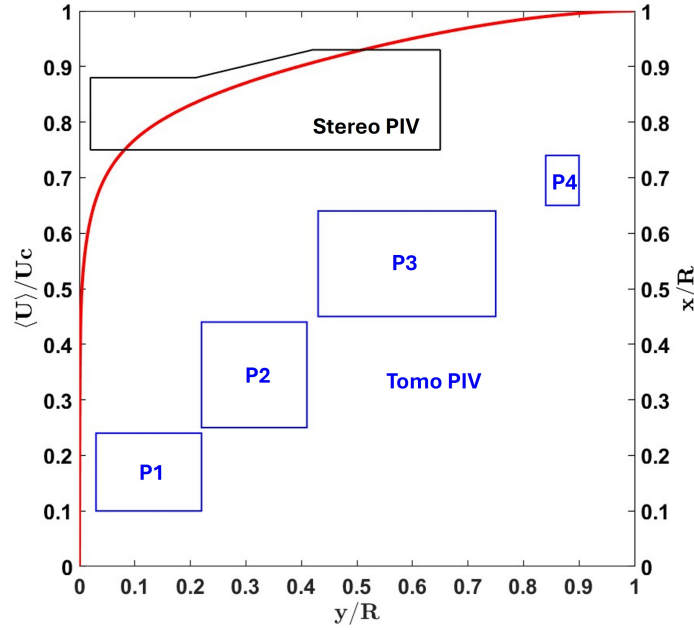


Figure 2. Schematic of the radial and streamwise extents of the regions **P1–P4** used in tomographic PIV measurements indicated by blue rectangles and superimposed on the mean streamwise profile obtained by direct numerical simulations for $Re_\tau = 12,000$ (Pirozzoli, 2024). The region used in the stereoscopic PIV measurements is indicated by the black distorted rectangle. All measurement regions are shifted in x -direction for clarity. See Table 2 for more details on the measurement regions, including the volume thickness into the board.

Herein we report on measurements acquired over distances from the wall in the range between $0.03R$ and $0.90R$, where $R = 45$ cm, is the pipe radius, over numerous sub-regions. However, our volumes do not reach within $0.02R$ from the wall, which is the focus on the accompanying paper by Schanz et al. (2026). Figure 2 shows the relative span of the different experiments, which were taken on different days. The detailed dimensions, sampling rates and flow scales are listed in Table 1. The camera arrangement for regions **P1** and **P2** (Figure 1.b) were acquired by shifting the camera supports closer to the window, without rearrangement of their angles, while **P3** required reducing their angle relative to the laser volume, thereby giving lower resolution of each pixel (Table 2). The measurements closest to the pipe centerline **P4** were taken with a different test section, which had different optical access with four smaller camera windows, as shown in Fig. 1(e). The droplets show diffraction-limited images of 2-4 px and should faithfully follow the flow, as we estimate the Stokes number for the largest air velocities as $St = \tau_p/\tau = 3.5 \times 10^{-4}$, using the characteristic flow-time of $\tau = R/U_C$. This also assumes low-Re Stokesian drag coefficient, ϕ of 1, the time constant of the particles is calculated to be $\tau_p = 3.3 \mu s$ using the following expression (Adrian & Westerweel, 2011).

$$\tau_p = \frac{(\rho_p - \rho_f)d_p^2}{18\rho_f\nu_f\phi}, \quad (1)$$

where, ρ_p, ρ_f are density of oil particles and air, d_p is the particle diameter which is here $\sim 1 \mu m$,

ν_f is the kinematic viscosity of the air. All physical properties are taken at 1 atm and 20°C.

Table 1. Summary of the experimental conditions and the tomographic and stereoscopic PIV recording parameters.

Here, U_C is the pipe centerline velocity, Re_τ is the friction Reynolds number, U_τ is the friction velocity, l_v is the viscous length scale, f_{pairs} is the camera acquisition frequency in double-frame recording mode, N_f is the number of double frames saved per run, Δt is the time interval between the two exposures in the frame-straddled image pair. L_c & W_c are the camera resolution aligned along the wall-normal and stream-wise directions respectively, and ν is the kinematic viscosity. Time-resolved (TR) acquisition is performed only in position P1 for $U_C = 4 \text{ m/s}$.

U_C m/s	Re_τ	U_τ m/s	$l_v = \nu/U_\tau$ μm	f_{pairs} kHz	N_f	Δt μs	$L_c \times W_c$ px $\times$ px
Positions P1–P3							
4.0	4,500	0.153	99.3	6.5	16,276	TR	2048 $\times$ 1952
4.9	5,400	0.183	83.1	4.2	16,276	84–140	2048 $\times$ 1520
10.6	10,800	0.365	41.6	4.2	16,276	42–70	2048 $\times$ 1520
20.2	19,600	0.664	23.0	4.2	16,276	20–35	2048 $\times$ 1520
40.3	37,300	1.258	12.1	4.2	16,276	10–18	2048 $\times$ 1520
50.2	45,900	1.550	9.8	4.2	16,276	8–14	2048 $\times$ 1520
Position P4 (Near Centerline)							
All Veloc.	—	—	—	3.3 & 1.1	25,454	10–120	2048 $\times$ 1952
Stereoscopic							
4.0	4,500	0.153	99.3	4.2	16,276	TR	2048 $\times$ 1520
All oth. Veloc.	—	—	—	4.2	16,276	18–90	2048 $\times$ 1520

The air-flow was seeded by intermittent pulses of theater smoke of Propantriol and Glycol aqueous mixture (Hazebase, Base L), resulting in about 1-micron droplets. The outlet from the smoke-machine was directed through a flexible tube into the tunnel immediately behind the test section and traveled around the closed circuit, through the air blowers, to finally enter the long straight pipe leading to the test section. Trial and error determined the number of puffs needed to seed the laser-volume for the full time-extent of each data collection, which usually has a duration of 3.5 s. The seeding density was kept high, ranging between 0.03 and 0.045 ppp. The data closest to the centerline (P4), was taken with bigger camera memory of 288 GB each, which allowed for 7.5 s duration, at 6.6 kfps.

The pulsed Nd-YAG double cavity pulsed laser (Photonics Industries DM2-532-150) was used in forward scattering, allowing imaging in a volume about 6 mm in depth over a 70 $\times$ 80 mm rectangle, as shown in Fig. 1(c). This rectangle stretches across the axial (x) and wall-normal (y) plane, relative to the pipe wall (located at $y = 0$), while the volume depth extends across the pipe az-

Table 2. Details on the radial locations of measurement locations and relevant tomographic and stereoscopic PIV parameters. The velocity volume in each measurement location is given by $L_x \times L_y \times L_z$.

Positions	P1	P2	P3	P4	Stereo
Radial extent y/R	0.03–0.22	0.22–0.41	0.43–0.75	0.84–0.90	0.02–0.65
Pixel resolution $\delta_p(\mu\text{m}/\text{px})$	35.7	35.5	53.2	18.9	64.3
Vector pitch δ_v (mm)	0.430	0.426	0.425	0.434	0.772
$L_x \times L_y$ (mm ²)	64×85	87×85	84×145	37×27	91×283
L_z (mm)	5.6	6.0	5.1	3.9	—
U_C (m/s)	Number of experimental runs				
4.0	2	—	—	—	2
4.9	4	4	2	2	2
10.6	4	4	3	4	4
20.2	8	8	4	2	5
40.3	5	4	4	7	8
50.2	4	4	5	6	4

imuthal direction (z). The imaging resolution was about $35 \mu\text{m}/\text{px}$, with a resulting final velocity grid of about 0.43 mm in all directions, as listed in Table 2.

While in a pipe flow configuration it is tempting to use a cylindrical coordinate system, for several reasons including the arrangements of the cameras and laser sheets for the current experiments, we primarily utilize a cartesian coordinate system with its origin at the wall. The x and y directions are in the streamwise and wall-normal directions, respectively. Locally and near the imaged regions, the z direction provides a good representation of the azimuthal (θ) direction, with some care to be exercised in interpreting the positive and negative orientation between them for both velocity and vorticity. It is also important to point out the opposite positive direction between radial velocity and the wall-normal velocity, which does not effect the normal stresses, but reverses the vorticity direction. In this arrangement of the coordinates, the pipe centerline is located at $y/R = 1$.

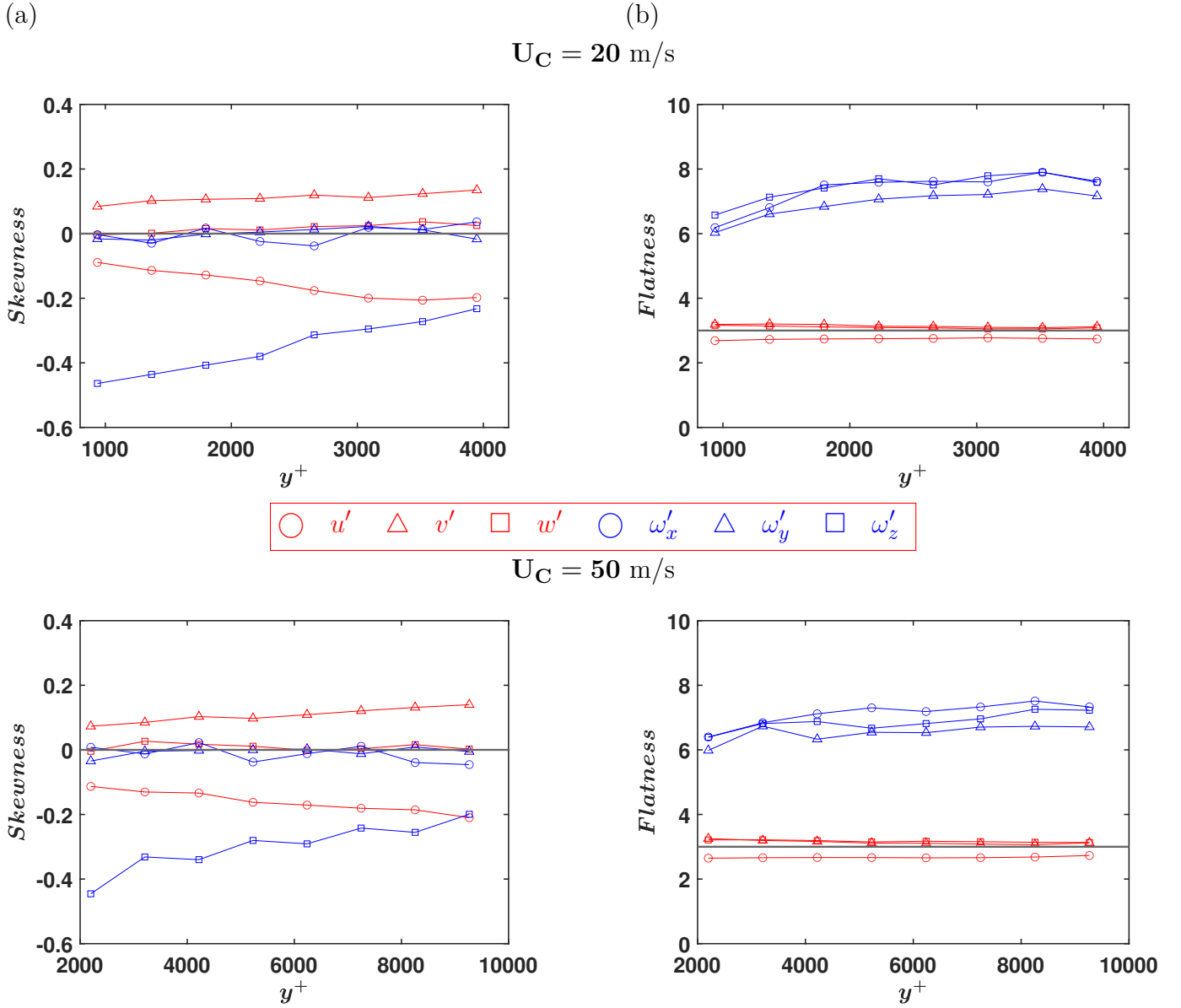


Figure 3. Skewness and flatness factors of the velocity and vorticity components for centerline velocity of $U_C = 20 \text{ m/s}$ ($Re_\tau = 19,600$) in the top row and the largest $U_C = 50 \text{ m/s}$ ($Re_\tau = 45,000$) is shown in the bottom row. The horizontal black lines in (a) indicate the zero skewness demanded by symmetric distributions, while the black lines in (b) mark the flatness factor of 3 for a Gaussian distribution. Measurements are from position **P1**.

3. Results

3.1. RMS and PDFs

Figure 3 shows the skewness and flatness of the velocity and vorticity components for the cases of largest centerline velocity of 20 m/s and 50 m/s. The results show near zero skewness for w' , ω'_x and ω'_y , as is expected by the statistical axisymmetry of the pipe flow and providing reassuring

indications of experimental accuracy. All three skewnesses deviate less than ± 0.04 from zero.

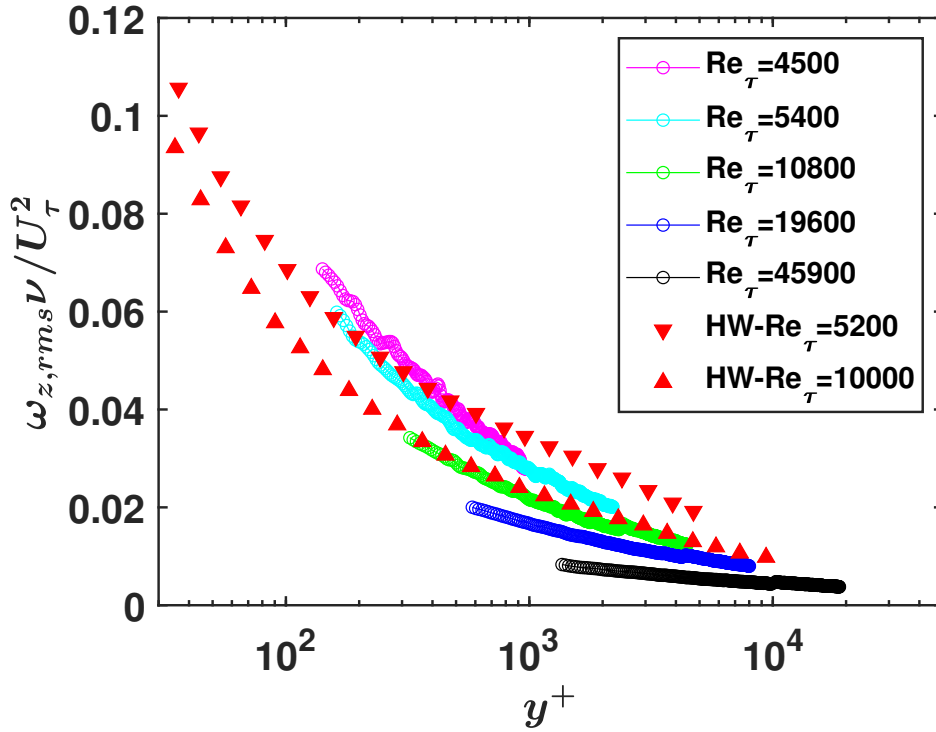


Figure 4. The rms of azimuthal vorticity compared to the multi-hot-wire measurements of Zimmerman et al. (2019) shown in red triangle symbols, over a range of Re_τ , shown for regions **P1** and **P2**.

On the other hand, ω'_z and u' , show negative skewness, while the v' skewness is slightly positive. The fluctuating velocities show flatness values close to the Gaussian value of 3. Herein, the 'primes' indicate the fluctuating components and the subscripts their directions. Hot-wire measurement on the centerline of CICLoPE over the same range of Re_τ report similar values of skewness and flatness for u' of -0.5 and 3.5, respectively. The vorticity components have much higher values between 6 and 8. The rms values of the vorticity are in good agreement with earlier measurements using multi-hot-wire probes in the same facility at lower Re_τ conditions by Zimmerman et al. (2019), as shown in Figure 4 for the azimuthal vorticity ω'_z . Zimmerman et al. (2019) measurements were performed up to $Re_\tau = 10,000$. The continued decrease in ω'_z with Re_τ is consistent with the multi-probe hot-wire measurements at lower Re_τ . However, the continued reduction in the viscous length-scale reduces the relative spatial resolution of the fixed velocity pitch of our measurements at the largest Re_τ . The possible effects of this on the rms values should be pinned down by future tests over a range of resolutions.

The velocity PDFs are near Gaussian, while for the azimuthal vorticity (Fig. 5b) they have stretched exponential tails over the range of Re_τ .

3.2. Vorticity alignment

The volumetric velocity measurements allow us not only to calculate the vorticity vector, but also the full rate-of-strain tensor at the internal points of the volume. First we find the directions of the principal rate-of-strain ordering them in strongest stretch (S) compression (C) and the intermediate (I) direction. Then we calculate the angle of the corresponding vorticity vector with respect to those coordinates. Figure 6(a) shows the strongest alignment of the vorticity with the intermediate strain rate, as is known for isotropic conditions (Hamlington et al., 2008). Strong alignment with the intermediate strain is also seen in turbulence through a contraction, however it is perpendicular to both compression and stretching directions with similar probability (Mugundhan et al., 2020), as is also seen with turbulent jets (Su & Dahm, 1996). Here we plot the PDF of the cosine of the alignment angle to account for the random probability on a sphere, taking a value of half. Figure 6(b) shows the alignment of the vorticity vector with respect to the pipe coordinates, streamwise (x), radial (y) and (z) directed in the azimuthal direction. The preferred alignment is here in the azimuthal direction, in agreement with the mean vorticity, while it is close to random in the other two directions. This alignment is quite weak, especially when compared to the extreme case of turbulence flowing through a contraction, as studied by Alhareth et al. (2024).

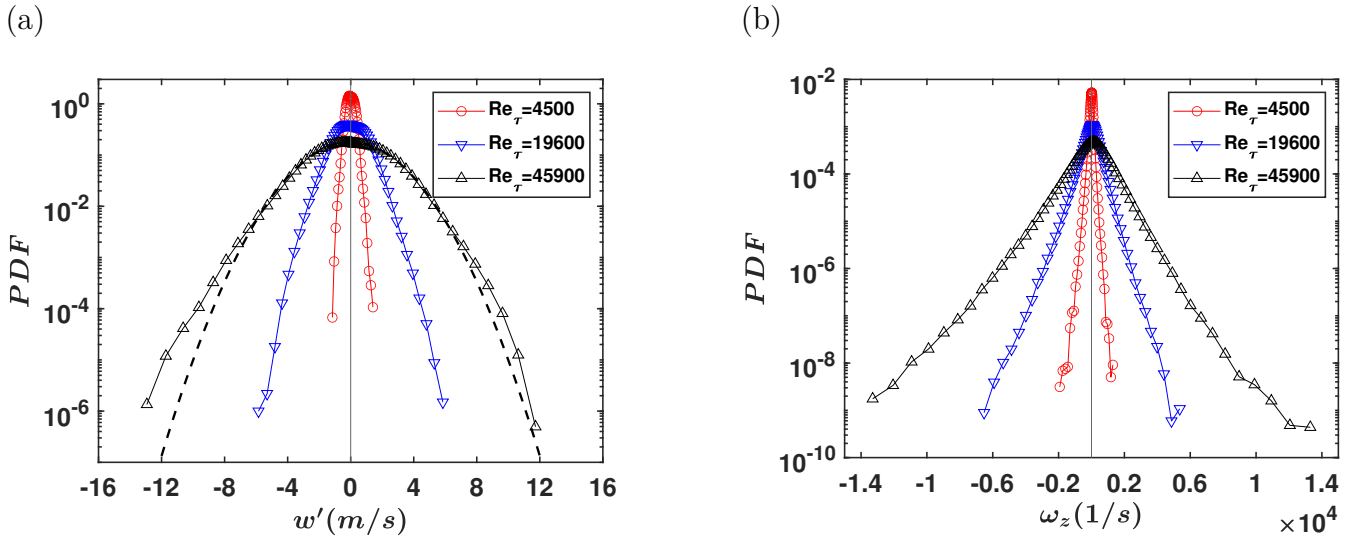


Figure 5. PDF of the (a) azimuthal velocity fluctuations and (b) azimuthal vorticity, for 5, 20 & 50 m/s centerline velocity, for different Re_τ up to 45,000. Measurements are all at 20 mm from the wall. The dotted black curve in (a) denotes the Gaussian distribution with zero mean and the same variance as the $U_C = 50$ m/s. The tails deviate slightly from the Gaussian distribution and it is flatter at the top.

3.3. Stereoscopic configuration

Limited experiments were conducted by rearranging the cameras to measure two adjacent stereoscopic planes, using two of the four cameras for each plane. This is done to simultaneously capture

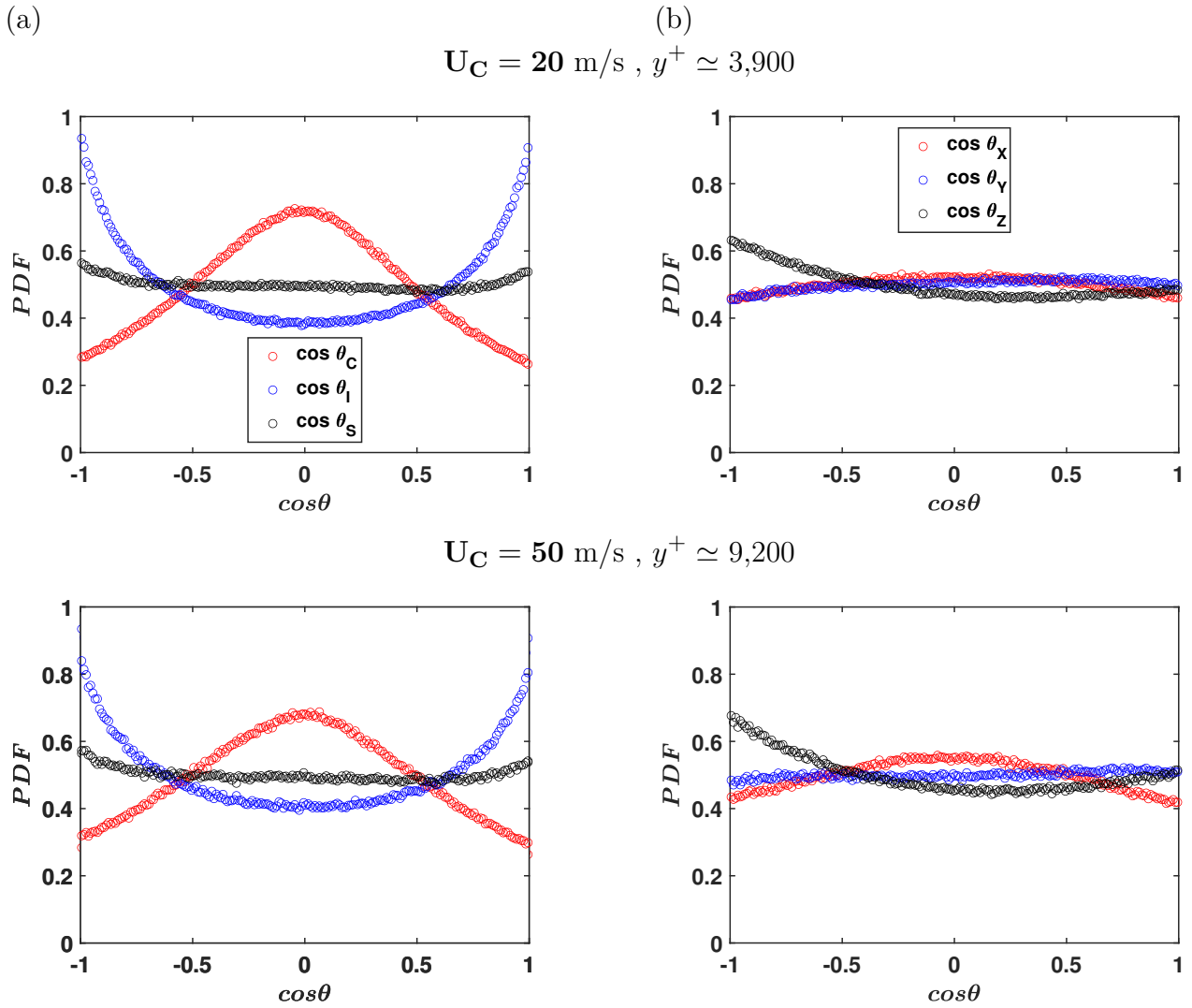


Figure 6. PDF of the cosine of the angle made by vorticity vector (a) with the principal directions of the local strain-rate tensor – compression (C), intermediate (I) and stretching (S), and (b) with the coordinates xyz . Measurements are all at 90 mm from the wall.

an area with a larger radial extent, from $0.02R$ to $0.65R$. This allows us to capture more of the time-evolution of the large-scale structures, but has the drawback of only capturing one component of the vorticity, i.e. ω_z out of the plane. This camera arrangement is shown in Figure 1(c), where the cameras are shifted as close together as possible. The top and bottom cameras on the left side capture the area closer to the wall, while the top and bottom cameras on the right capture the area closer to the centerline. The Davis program (LaVision) allows simultaneous calculation of velocity over the combined area, as shown in Figure 7. The resulting area of velocities has an irregular shape owing to the asymmetric arrangement of the cameras. This is unavoidable with the current camera size and extent of the glass window. The thickness of the laser for these experiments was narrowed to $\simeq 3$ mm.

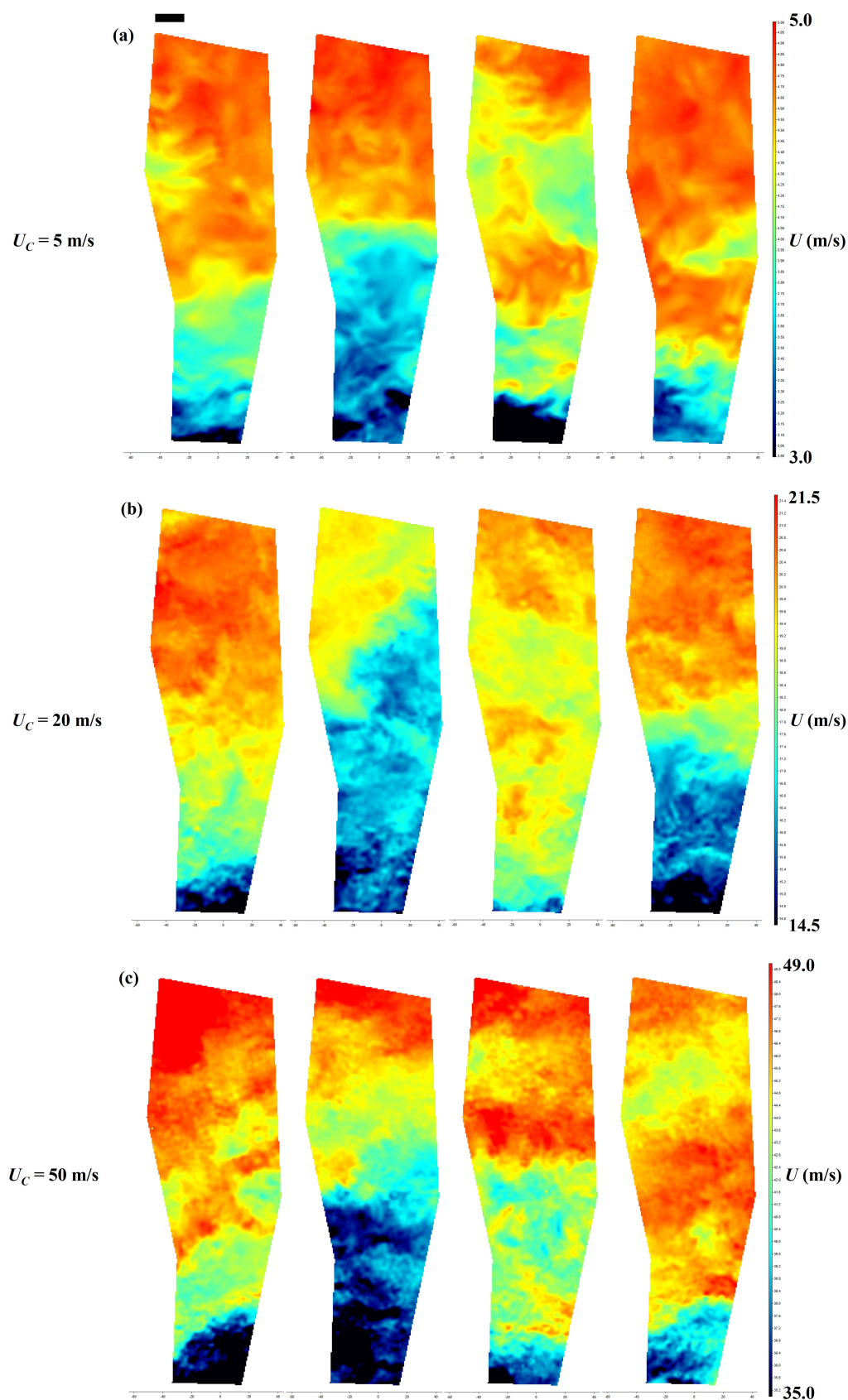


Figure 7. Randomly selected sequences of contours of instantaneous streamwise velocity, $U(x, y)$ (m/s), shown at four independent times, for three different centerline velocities (a) $U_C = 5 \text{ m/s}$, (b) 20 m/s and (c) 50 m/s . The scale bar shown in (a) represents 20 mm.

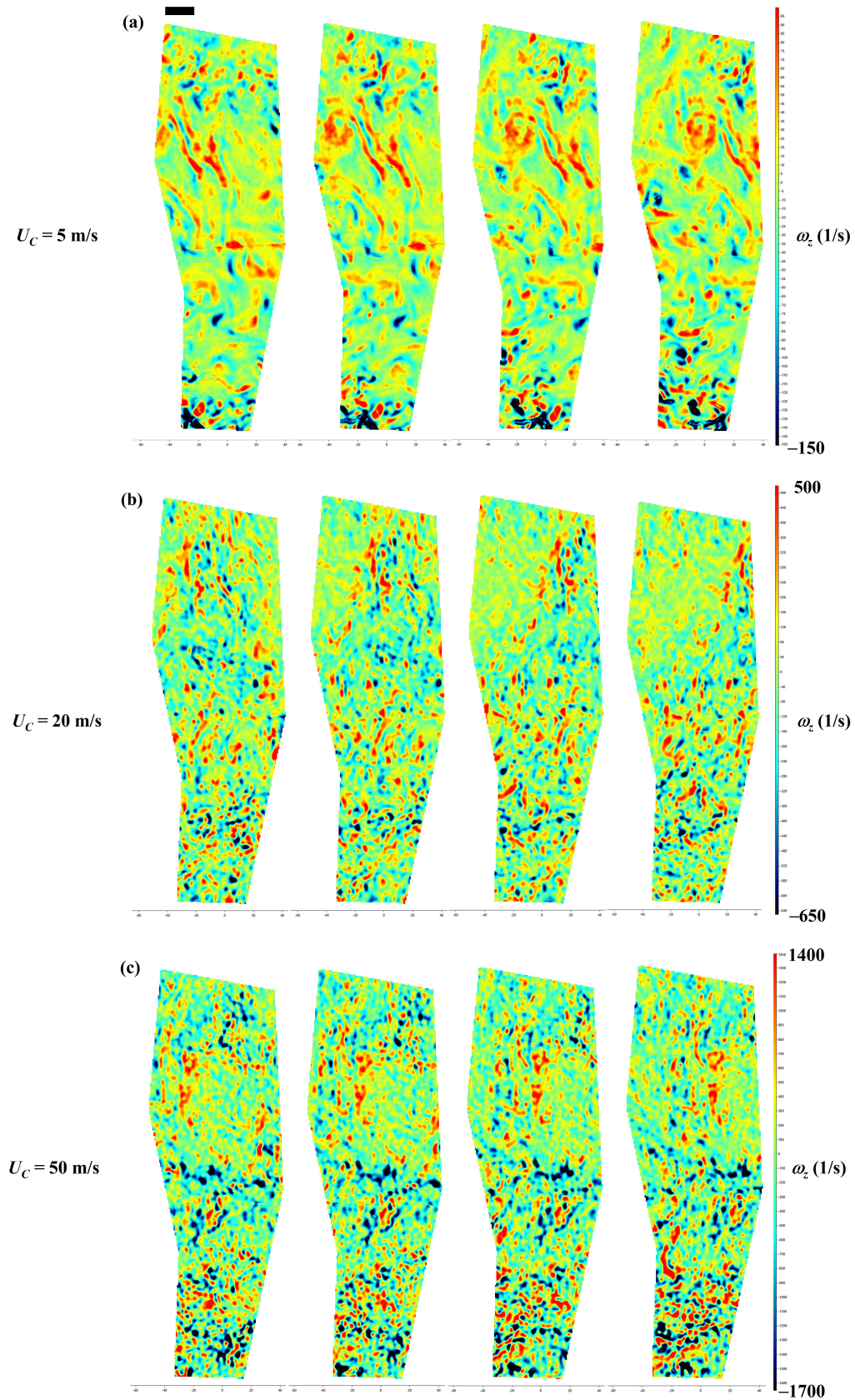


Figure 8. Time evolution of vortices visualized by azimuthal vorticity, ω_z (s^{-1}) for centerline velocities $U_C = 5 \text{ m/s}$ (a), 20 m/s (b) and 50 m/s (c). The snapshots are separated by (a) 15, (b) 4 and (c) 1 volumes. The scale bar shown in (a) represents 20 mm and the two axis are of equal scale.

Figure 7 shows typical streamwise velocity fields, highlighting the presence of uniform momentum zones (UMZs) first discovered by Meinhart & Adrian (1995) in the flat-plate boundary layer. UMZs were subsequently the focus of numerous studies, both in boundary layers (de Silva et al., 2016; Laskari et al., 2018) and pipe flow (Chen et al., 2020). UMZ analysis in channel flows by Kwon et al. (2014) revealed the existence of a quiescent core with near-uniform velocity and minimum turbulence. The figure shows random examples of the streamwise velocity, which clearly show numerous UMZs. Stacking frames in time, one can estimate the streamwise extent of each zone and characterize their prominence. This sets up the dataset for future analysis on the time evolution of turbulent superstructures and their relationship with the attached eddy hierarchy very near the wall and the UMZs, which has been investigated previously only through 2D-2C snapshot PIV (Deshpande et al., 2023).

Figure 8 shows the azimuthal vorticity ω_z over a sequence of four time-steps, demonstrating how we can follow the turbulent vortical structure in time. The minimal changes in the advected vortical blobs, supports the accuracy of the measurements. For the lowest velocity (5 m/s), we show only every 15th volume, while for the fastest (50 m/s), we show every volume. With a fixed video frame-rate, the flow traverses the illuminated area in fewer frames at the highest centerline velocity. Note the large change in the strength of the vorticity fluctuations for the different Re_τ , where we see a range $\omega_z = [-150, 100]$ 1/s for $Re_\tau = 5,400$; $[-650, 500]$ 1/s for $Re_\tau = 19,600$, and $[-1700, 1400]$ 1/s for $Re_\tau = 45,900$, showing approximately a linear dependence. However, the most striking differences are the longer vortical filaments for the lowest $Re_\tau = 5,400$, while the two larger Re_τ have thinner and more circular structures, and the vortical pattern very near the wall changes with Reynolds number. The maximum and minimum colours also skew towards negative ω_z , of the same sign as the vorticity of the mean velocity profile, even though its strength is only $\Omega_z \sim U_C/R = 8.9 - 112 \text{ s}^{-1}$, which is $\sim 6\%$.

On the other hand the overall structure and magnitudes of the vortical patches is highly intermittent in space and time, which will require characterizing at the enstrophy intermittency (Zimmerman et al., 2019).

4. Discussion and Conclusions

Our time-resolved Tomo-PIV measurements can reach to the highest $Re_\tau \sim 45,000$ at $U_C \simeq 50 \text{ m/s}$, demonstrating the unique capabilities of the CICLoPE facility. The one-micron seeding theater-smoke droplets give sufficient spatial resolution, when combined with pixel resolution down to $19 \mu\text{m}$. Resolving the full rate-of-strain tensor presents a broad range of opportunities to study vortical dynamics, coherent structures, intermittency and dissipation, at Re_τ out of reach of the current numerical simulations. Measurements closer to the solid wall, are pursued by an accompanying paper of Schanz et al. (2026). Future publications based on the large volume of data from

the current experiments will also report on excellent comparisons with the more recent hot-wire data from CICLoPE by Nagib et al. (2026) that revealed Reynolds number independence of the streamwise normal stress on the pipe centerline for Re_τ larger than around 10,000.

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