Time resolved, near wall PIV measurements in a high Reynolds number turbulent pipe flow

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Outline

• Project aims
• Background on pipe flow facility CICLoPE
• Implementation of high-speed PIV on facility
• Sample results
  • mean profiles
  • variances, co-variance
  • spectra, space-time-correlations, etc.

Note: This is work in progress!!
Motivation

• near wall flow structure of pipe flow so far has not been characterized well quantitatively through measurements, mainly due to finite size of probes

• for high-Re hotwire data is only available for wall distances $y > 20^+$ (e.g. SuperPipe Princeton)

• DNS only available at low Reynolds numbers
  - for pipe flows $Re_{\tau,\text{max}} \leq 1050$ (Satake et al, HPC, 2000),
  - for channel flow $Re_{\tau,\text{max}} = 5200$ (Lee & Moser, JFM, 2015)

• DNS difficult to perform using spectral methods due to singularity at center of pipe.

• CICLoPE pipe facility offers combination of high Reynolds number and viscous scales that can be experimentally captured → application of PIV becomes possible using standard imaging

CICLoPE = Ccenter for International Cooperation in Long Pipe Experiments
www.ciclope.unibo.it
Reynolds number range for various pipe facilities

Talamelli et al. “CICLoPE—a response to the need for high Reynolds number experiments”, Fluid Dyn. Res. 41 (2009) 021407
Location: Former WW2 Caproni Aircraft tunnel complex

used for Mushroom farming until recently
CICLoPE Facility

Conditions

<table>
<thead>
<tr>
<th>Condition</th>
<th>$U_m$ [m/s]</th>
<th>$Re_D$ [-]</th>
<th>$R^+$ [-]</th>
<th>$L^*$ [µm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>DNS (Highest in 2009)</td>
<td>1.4</td>
<td>84,000</td>
<td>2,200</td>
<td>222</td>
</tr>
<tr>
<td>Appearance of log region</td>
<td>11</td>
<td>0.66M</td>
<td>13,000</td>
<td>34</td>
</tr>
<tr>
<td>Design point</td>
<td>38</td>
<td>2.3M</td>
<td>40,000</td>
<td>11</td>
</tr>
<tr>
<td>Maximum power</td>
<td>70</td>
<td>4.3M</td>
<td>71,000</td>
<td>6</td>
</tr>
</tbody>
</table>

- length: 115 m
- diameter: 0.9 m ±0.5 mm
- surface roughness: < 10 µm
- $Re_T : 3000 – 40000 (60000)$
- Viscous scales: 100 … 10 µm
- $U_{mean} = \sim 5 \ldots 40$ m/s (55 m/s)
Measurement insert

- 45° mirror
- Plane window (camera)
- Concave window (laser)
Setup for near-wall PIV measurements

Light source:
- Darwin Duo (2x40W)
- Pulse width ~300ns
- max freq. 10 kHz
Vibrations

- present at $U \geq 30$ m/s
- tracked using correlation approach
- image shifting before PIV analysis

$U_o = 30$ m/s

$U_o = 40$ m/s
Time-record of stream-wise velocity profile

Reₜ = 20,000

U₀ = 22 m/s  1000 of 70000 samples  10 kHz sample rate

also have wall-normal velocity component (and vorticity ωᵪ )
Mean velocity profiles

\[ u^+ = \frac{1}{\kappa} \log(y^+) + B \]

- DNS \( \text{Re}_\tau = 5200 \)
- \( \text{Re}_\tau = 5386 \)
- \( \text{Re}_\tau = 11729 \)
- \( \text{Re}_\tau = 19918 \)
- \( \text{Re}_\tau = 27997 \)
- \( \text{Re}_\tau = 39985 \)

DNS data from: M Lee and RD Moser, Direct numerical simulation of turbulent channel flow up to \( \text{Re}_\tau = 5200 \), 2015, JFM 774, pp. 395-415
Mean velocity profiles – incl. hotwire data

\[ U^+ = \frac{1}{\kappa} \log(y^+) + B \]

**SuperPipe data from**
- Hultmark et al. PRL (2012)
- Hultmark et al. JFM (2013)

- \( \kappa = 0.41 \)
- \( B = 5.1 \)
Reynolds stress profiles

DNS data from: M Lee and RD Moser, Direct numerical simulation of turbulent channel flow up to $Re_T = 5200$, 2015, JFM 774, pp. 395-415
Reynolds stress profiles, incl. hotwire data

Hotwire data from

\[ \langle u'v' \rangle \]

- **Hotwire, \( Re_\tau = 15000 \)**
- **Hotwire, \( Re_\tau = 25000 \)**
- **Hotwire, \( Re_\tau = 40000 \)**
Reynolds stress profiles, incl. SuperPipe data

SuperPipe data from Hultmark et al. PRL (2012)
Hultmark et al. JFM (2013)
Influence of sampling window on inner peak height

**PIV sample size**
- 32 x 12 pixel
- 48 x 8 pixel
- 64 x 6 pixel
- 96 x 6 pixel
- 128 x 6 pixel

![Graph showing the influence of sampling window on inner peak height](image-url)
Joint-PDFs : Pipe vs. Flat Plate Turbulent BL

\( \text{Re}_\tau = 20,000 \ (U_0 = 22 \text{ m/s}) \)

\( y = 0.3 \text{ mm} \ (13y^+ ) \)
\( y = 0.9 \text{ mm} \ (40y^+ ) \)
\( y = 8.8 \text{ mm} \ (400y^+ ) \)
\( y = 13^+ \)
\( y = 40^+ \)
\( y = 400^+ \)

\( \text{Re}_\tau = 830 \ (U_\infty = 5 \text{ m/s}) \)

\( y = 0.9 \text{ mm} \ (13y^+ ) \)
\( y = 2.8 \text{ mm} \ (40y^+ ) \)
\( y = 21.4 \text{ mm} \ (300y^+ ) \)
\( y = 300^+ \)
Summary – High-Re turbulent pipe flow measurements

• first application of PIV in new pipe flow facility CICLoPE (in operation since 2015)

• PIV measurements at Reynolds number range $Re_T = 5,000 \ldots 40,000$

• imaging with spatial resolution of $O(10\mu m)$ resolves viscous sublayer

• statistical convergence through multiple time-records with each up to 70,000 samples

• inner peak grows with $Re_T$ (similar to ZPG-Turb. BL)

• work in progress:
  • extract unsteady wall-shear stress from images
  • detailed spectral analysis, space-time-correlations, length scales,…
  • …