Spatially and temporally resolved 2C-2D PIV in the inner layer of a high Reynolds number adverse pressure gradient turbulent boundary layer

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ABSTRACT

A joint experiment was performed in May 2015 in the framework of the European Project EuHIT: "European High performance Infrastructures in Turbulence". One of the aims was a detailed study of a high Reynolds number turbulent boundary layer flow under adverse pressure gradient (APG-TBL) to determine the effect of the pressure gradient on the spatio-temporal character of structures in the inner layer. Highly spatially resolved time series of up to 38 s duration of the streamwise and wall-normal velocity component were measured using 2C-2D PIV with single-exposed image pairs acquired at frequencies up to 6.7 kHz. The domain of these 2C-2D velocity field measurements spanned 5 x 25 mm\textsuperscript{2} corresponding to a domain of up to 85+ x 426+ with the spatial resolution of the velocity measurements ranging from 0.4+ to 0.7+. Using these highly spatially and temporally resolved velocity measurements, time series of the wall-shear stress, spectra of the velocities, statistics and other pertinent characteristics of the APG-TBL were extracted and analysed. 2C-2D PIV using a sCMOS camera with 2560 x 2160 px resolution and 16 bit dynamic range was undertaken in streamwise–spanwise planes spanning 14.6 x 17.3 mm\textsuperscript{2}, which corresponds to a domain of up to 250+ x 300+. The spatial resolution of these velocity measurements is 0.9+. The camera was equipped with a Zeiss lens of 100 mm focal length with a teleconverter. f2 was used for these experiments, resulting in an estimated depth-of-field of 170 µm and a diffraction limited diameter of approximately 10 µm. These measurements provide pertinent spanwise characteristics of the low and high momentum zones at different wall-normal distances in the APG-TBL.
1 Introduction

Adverse pressure gradient turbulent boundary layers (APG-TBL) at high Reynolds number in contrast to zero pressure gradient turbulent boundary layer (ZPG-TBL) and channel flows are not well understood, not even from a scaling point of view. This is partly due to the lack of comprehensive experimental data at sufficiently high Reynolds number. Very often, the facilities are too small to reach high Reynolds numbers and to let the boundary layer develop enough to reach some state of equilibrium where theoretical approaches can be relevant. Moreover, measurements are generally quite limited leading to a lack of detailed characterization of the flow itself but also of the boundary conditions, which makes the data very difficult to use in practice, both for physical understanding and for models validation. A thorough review of the relevant background to the present investigation is presented in Kähler et al. (2016) and therefore not repeated here. Extensive 2C-2D large field of view PIV and 3C-2D stereo PIV measurements reported in Kähler et al. (2016) were complement with time resolved near wall velocity profiles and planar near wall measurements performed in order to determine the viscous and buffer layer velocity fields at some specific locations along the model. The aim of the present paper is to present this latter components of the unique experiment which was a

2 Experimental Methodology

2.1 APG-TBL Setup in the LML High Reynolds Number Boundary Layer Wind Tunnel

The experiments were performed in a Göttingen type high Reynolds number boundary layer wind tunnel at LML which has a test section length of 20.6 m in the streamwise direction (x-direction) and a cross-section 2 m wide and 1 m high. The wind tunnel is made of a metal frame work with large exchangeable windows of high quality plexiglass along the whole test section length providing outstanding optical access. This wind tunnel test section has a custom designed floor-mounted model as shown in Fig. 1 to generate a high Reynolds number turbulent boundary layer in an adverse pressure gradient environment over a relatively large streamwise extend.

Fig. 1 a) Side view of the experimental custom designed floor-mounted model installed in the wind tunnel showing the measurement area of a TBL with adverse pressure gradient marked in green colour, b) Plan view of the experimental custom designed floor-mounted model.

In Fig. 1 the flow is from left to right. The floor-mounted model consists of a 2D-bump geometry of \( \sim 1.25 \)
length, which reduces the cross-sectional area, followed by a 2.2 m flat plate in the direction of the flow with a slight positive angle of attack and a second flat plate with a length of 3.5 m and a -5° inclination down to the horizontal wall. One should notice that the plate is made from several individual pieces so that small interface imperfections exist. The free-stream flow velocities were set to \( U_\infty = 5 \text{ m/s} \) and \( U_\infty = 9 \text{ m/s} \) at the very beginning of the test section. In this paper only the results corresponding to \( U_\infty = 5 \text{ m/s} \) are presented. The boundary layers first develop at approximately zero pressure gradients along the walls inside the wind tunnel until the flow reaches the bump that follows the first flat plate segment. Here a favourable pressure gradient accelerates the flow up to the point where the long flat plate starts with a negative inclination angle inducing an adverse pressure gradient. The length of the measurement domain of the multi-camera 2C-2D-PIV measurement reported in Kähler et al. (2016) is highlighted by the green area. It is 3.5 m long to ensure the possibility of capturing very large scale turbulent structures with lengths of more than 10 boundary layer thicknesses, \( \delta \). Further details of the global experimental flow conditions for this experimental campaign in the high Reynolds number boundary layer wind tunnel at LML are provided in Kähler et al. (2016) and are not repeated here. All PIV experiments used the same seeding from a water/glycol smoke generator which produced seeding particles with a mean diameter of \( d_p \approx 1 \mu m \).

The results reported in this paper relate to measurements taken at locations B, 1, 3 and 4 shown in Fig. 2. Specifically, time series of 2C-2D PIV in a streamwise–wall-normal (\( x - y \)) plane along the spanwise centreline of the wind tunnel test section were measured at all of these locations, while the 2C-2D PIV in the streamwise–spanwise (\( x - z \)) planes located normal to the inclined model floor were measured at location 1 only. The distance of the APG locations relative to the start of the sloping APG plate are: 1: 0.483 m, 3: 1.733 m and 4: 2.358 m.

![Fig. 2 Side view of wind tunnel test section with APG-Model and measurement positions.](image)

### 2.2 2C-2D PIV Experimental Set-up and Analysis in \( x - y \) Centreline Plane

The temporally resolved 2C-2D velocity field in a \( x - y \) plane along the centreline of the wind tunnel was measured using the high-speed long-range micro-PIV method described in Willert (2015). An approximately 5 mm wide measurement area located at the wind tunnel centreline at positions B, 1, 3 and 4 was illuminated with a pair of externally modulated continuous wave lasers (Kvant Laser, SK) with a combined output power of nearly 10 W at a wavelength of 520 nm. Focussing lenses narrowed the 5 mm wide light sheet to a thickness of about 200-300 \( \mu m \) before passing through an anti-reflection-coated 3 mm thick glass window at the centre of the acrylic glass panel of the APG-TBL section. A telephoto lens (Zeiss 300mm/f2.8) with a 100 mm extension tube was used to image the near wall region at a sufficiently high magnification of \( M = 0.44 \). Laser illuminated particle images were acquired using a high-speed CMOS camera (PCO, Dimax-S4) with a pixel pitch of 11 \( \mu m \) (corresponding to 25 \( \mu m / \text{pixel} \) in object space). The set-up is depicted in Fig. 3. Synchronisation between the modulated laser and camera was provided through a separate pulser unit (Arduino MEGA 2560). The camera was mounted with a 90° sideways rotation in order to achieve the highest possible sensor readout rates. To account for the increase in magnification and reduction of the light sheet thickness, the seeding rate was increased by a factor of roughly 3 to 4 on the smoke generator relative to the other PIV experiments reported here and in Kähler et al. (2016). At each measurement location a minimum of two sequences consisting of
more than 50,000 images were acquired at the free-stream flow condition of $U_\infty = 5 \text{ m/s}$. The most relevant parameters are summarised in Table 1.

![Image](a) ![Image](b)

Fig. 3 Left: High-speed camera with 300 mm lens. Right: laser light sheet introduced from below the wind-tunnel through an anti-reflection coated thin glass window.

Figure 4 provides an example of the image quality achievable with the described setup by showing a superposition of four consecutive images separated in time by 150 µs with a laser pulse duration of 20 µs. The wind tunnel floor can be located through the mirrored particle images near the bottom of the image at $U_\infty = 5 \text{ m/s}$. Slight particle streaking can be observed in the faster moving upper image area. The image sequences were processed using a multigrid/multipass 2C-2D cross-correlation PIV analysis algorithm Willert and Gharib (1991); Soria (1996). Using a coarse-to-fine pyramid approach Sciacchitano et al. (2012) with intermediate validation (normalized median filter and smoothing), the final interrogation window size is typically $64 \times 8$ or $32 \times 8$ pixels, corresponding to $1.6 \times 0.2 \text{ mm}^2$ or $0.8 \times 0.2 \text{ mm}^2$ with a sample overlap of 75%. The large aspect ratio was chosen to achieve optimal wall-normal spatial resolution in the recovered velocity profiles. Validation rates exceed 99.9% along the midline of the PIV recordings.

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<tr>
<td>Free-stream velocity</td>
<td>$U_\infty$</td>
<td>5 m/s</td>
</tr>
<tr>
<td>Laser pulse separation</td>
<td>$\Delta t$</td>
<td>100 / 150 µs</td>
</tr>
<tr>
<td>Laser pulse duration</td>
<td>$pw$</td>
<td>20 / 25 µs</td>
</tr>
<tr>
<td>Image size (PCO.Dimax-S4)</td>
<td>$W \times H$</td>
<td>$178 \times 288 \text{ px}^2$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$200 \times 1008 \text{ px}^2$</td>
</tr>
<tr>
<td>Sample rate (PCO.Dimax-S4)</td>
<td></td>
<td>1000, 2000, 6667 Hz</td>
</tr>
<tr>
<td>Number of acquired image pairs</td>
<td>$N$</td>
<td>63,464 / 251,583</td>
</tr>
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Table 1 High-speed image acquisition parameters (highlighted values indicate the most frequently used configuration).

2.3 2C-2D PIV Experimental Set-up and Analysis in $x - z$ Planes

The velocity field in $x - z$ planes at position 1 shown in Fig. 2 were measured using 2C-2D PIV and depicted in Fig. 5 (a). A Nd:YAG laser producing $2 \times 200 \text{ mJ}$ pulses at 532 nm was used for generating a thin laser
light-sheet in a plane parallel to the plane of the inclined flat plate as shown in Fig. 5 (b). The laser light sheet position normal to the inclined plane was controllable using a mirror mounted on a micrometer stage as depicted in Fig. 5 (b). The micrometer stage has a resolution of 10 μm with an uncertainty of 5 μm at the 95% confidence level. The tunnel was heavily seeded using a water/glycol smoke generator (a few times more than the seeding required for the time-resolved PIV measurement) in order to have sufficient particles in the inner layer planes very close to the wall. Single-exposed laser illuminated particle images were acquired using a sCMOS camera with 2560 × 2160 px resolution and 16 bit dynamic range fitted with a 100 mm focal length Zeiss lens and a teleconverter. The f number was set at 2 for these experiments, which resulted in an estimated depth-of-field of 170 μm and a diffraction limited diameter of approximately 10 μm. The imaging set-up resulted in 6.7 μm/px in object space. The camera was mounted on a micrometer stage that allowed the imaging plane to be positioned with a resolution of 10 μm and an uncertainty of 5 μm at the 95% confidence level. 10,000 statistically independent 2C-2D PIV velocity fields were acquired for each wall-normal location. The PIV images were analysed using the multigrid/multipass approach of Soria (1996), resulting in vector fields of 313 × 263 vectors. Table 2 summarises the pertinent measurement parameters for the 2C-2D wall-normal planar PIV wall-shear stress measurements. The superscript denotes viscous units.
Table 2 Experimental conditions for PIV measurements in x-z planes, i.e. planes that are parallel to the inclined wall.

<table>
<thead>
<tr>
<th>$U_\infty$</th>
<th>5 m/s</th>
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<tr>
<td>$y$ (µm)</td>
<td>347.0 896.0 1734.0</td>
</tr>
<tr>
<td>$y^+$</td>
<td>5.9 15.5 28.8</td>
</tr>
<tr>
<td>Field of view (mm × mm)</td>
<td>14.6 × 17.3</td>
</tr>
<tr>
<td>Field of view (°)</td>
<td>248 × 295</td>
</tr>
</tbody>
</table>

3 Results and Discussion

3.1 2C-2D PIV along the $x-y$ Centreline Plane

High repetition 2C-2D PIV measurements were undertaken at the positions identified as B, 1, 3, and 4 with high spatial resolution. Figure 6 shows the mean velocity at location B where an zero pressure gradient turbulent boundary layer (ZPG-TBL) is developing, where $Re_x = 1,842$. The results show that the closest measurement to the wall is approximately at $y^+ \approx 1$. The mean velocity and mean square turbulence velocity fluctuations computed from the instantaneous 2C-2D PIV measurements, scaled in viscous units, in the viscous and lower buffer layer are shown by the dots in Fig. 6 to clearly demonstrate the high spatial resolution of these measurements, while the blue lines correspond to the measurements within the measurement domain of these 2C-2D PIV. The mean velocity compares very well with the recent DNS of ZPG-TBL by Sillero et al. (2013) depicted in red and corresponding to a location where $Re_x = 1,437$. The peak in the mean square turbulence velocity fluctuations of the 2C-2D PIV is located at $y^+ \approx 15$ and also compares very well within the experimental uncertainty with the corresponding DNS results of Sillero et al. (2013).

Figure 7 shows a compilation of some pertinent results of these 2C-2D PIV measurements for the ZPG-TBL position and the three APG-TBL positions. When scaled in viscous scales, the mean velocity profiles
Fig. 6 Streamwise mean and turbulence velocity fluctuations at location B scaled in viscous units, corresponding to a zero pressure gradient turbulent boundary layer (ZPG-TBL) at $Re_\tau = 1,842$. The blue lines are the 2C-2D PIV with the dots shown in the viscous and lower buffer layer to indicate the measurement locations there and the measurement spatial resolution. The red lines are DNS data of a zero pressure gradient turbulent boundary layer at $Re_\tau = 1,437$ by Sillero et al. (2013). The black dashed line corresponds to $U^+ = y^+$. 

differ between the ZPG-TBL and APG-TBL and there are differences within the APG-TBL region as can been observed in Fig. 7 (b) - (d). The streamwise turbulence fluctuations differ more significantly. The APG-TBL peak in $<u^+ u^+>$ is larger in the APG-TBL region compared to the peak in the ZPG-TBL and increases downstream in the APG-TBL, as well as moving away from the wall and broadening in terms of viscous units.

3.2 2C-2D PIV in $x-z$ Planes

The 2C-2D velocity field was measured in three $x-z$ planes which were locally parallel to the wall at position 1. Figure 8 shows the mean velocity measured at position 1 using 2C-2D PIV in the $x-y$ plane indicating the positions of the three $x-z$ 2C-2D PIV measurement locations normal to the wall. Typical instantaneous turbulent streamwise velocity fluctuations are also shown in Fig. 8. These clearly show the well known low speed velocity streaks, particularly well depicted at $y^+ = 5.9$ in Fig. 8.

A summary of some of the pertinent main results of the 2C-2D $x-z$ PIV are shown in Fig. 9. In Fig. 9 (a) - (c) typical instantaneous streamline patterns with grey contours of the streamwise velocity fluctuations. At $y^+ = 5.9$ shown in Fig. 9 (a), it seems that the streamlines converge in regions of low speed streaks, which are indicated by the dark grey regions. This seems to be the case also further away from the wall at $y^+ = 15.5$ shown in Fig. 9 (b), but is not so obvious at $y^+ = 28.8$, which is shown in Fig. 9 (c). The streamline pattern as observed by an observer moving with the mean velocity of each respective plane shows that the low speed streaks are accompanied on either spanwise side by focal topologies as shown in Fig. 9 (d) indicative
Fig. 7 Streamwise mean and turbulent fluctuation velocity for positions B, 1, 3 and 4 shown in (a) - (d) respectively. The black dashed line corresponds to $U^+ = y^+$ in (a) - (d). Streamwise velocity Spectra as a function of wall-normal distance $y^+$ in viscous units for positions B, 1, 3 and 4 shown in (e) - (h) respectively.

of wall-normal vortices. This structure is observable at all wall-normal positions as clearly observable in Fig. 9 (e) and Fig. 9 (f), with the length scale of the foci increasing with increasing wall-normal distance.

The joint probability density function (JPDF) between the streamwise and spanwise turbulence fluctuations are shown in Fig. 9 (g) - (i) for the three wall-normal positions. Although the structure of the JPDF changes significantly as the distance from the wall increases, all exhibit symmetry in the spanwise direction. The peak in the JPDF is found to be a negative velocity fluctuation at $y^+ = 5.9$ as shown in Fig. 9 (g) consistent with the predominance of low speed streaks in this inner viscous region of the APG-TBL at position 1. The JPDF which is skewed in towards negative velocity fluctuations at $y^+ = 5.9$ becomes less skewed away from the wall and is more symmetric at $y^+ = 28.8$ as shown in Fig. 9 (i). This trend is also shown in the marginal PDF of the turbulent streamwise velocity fluctuations which are shown in Fig. 9 (j) - (l) corresponding to $y^+ = 5.9, 15.5$ and 28.8 respectively. The undulations observed in the JPDF and PDF for $y^+ = 15.5$ and 28.8 are most likely due to pixel locking. Pixel locking at the wall-normal location of $y^+ = 5.9$ in Fig. 9 (g) and (j) is not observable, most likely due to the larger relative wall-normal averaging domain at this wall-normal location.

4 Concluding Remarks

This paper reports some preliminary results of two of the components of a unique experiment of a high Reynolds number adverse pressure gradient turbulent boundary layer flow which was the result of a collaboration between five international teams. Specifically presented here are the results of highly spatially resolved time series of up to 38 s duration of the streamwise and wall-normal velocity component measured using 2C-2D PIV with single-exposed image pairs acquired at frequencies up to 6.7 kHz. The domain of these 2C-2D velocity field measurements spanned $5 \times 25$ mm$^2$ corresponding to a domain of up to $85^+ \times 426^+$ with the spatial resolution of the velocity measurements ranging from $0.4^+$ to $0.7^+$. Using these highly spatially and temporally resolved velocity measurements, time series of the wall-shear stress, spectra of the velocities, statistics and other pertinent characteristics of the APG-TBL were extracted and presented. 2C-2D PIV using a sCMOS camera with $2560 \times 2160$ px resolution and 16 bit dynamic range was undertaken in streamwise–spanwise planes spanning $14.6 \times 17.3$ mm$^2$, which corresponds to a domain of up to $250^+ \times 300^+$. These results allow the extraction of the flow topology and its relationship to the low speed streaks. JPDFs between the streamwise and spanwise velocity components were also computed using these 2C-2D velocity fields, which
Fig. 8 Mean velocity profile at position 1: 0.483 m, with indication of the wall-normal locations of the $x-z$ PIV velocity measurement planes and corresponding typical instantaneous fluctuating velocity fields in those planes.

showed that these JPDFs are symmetric in the spanwise direction and are skewed towards negative streamwise velocity fluctuations at $y^+ = 5.9$, but are approximately symmetric by $y^+ = 28.8$.

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References


Fig. 9 The results in (a) - (c) show typical instantaneous streamline patterns with grey contours of the turbulent streamwise velocity fluctuations. (d) - (f) show the corresponding streamline pattern as seen by an observer moving with the mean streamwise velocity at the corresponding wall-normal distance, Flow is from left to right in all of these. The joint probability density function (JPDF) between the streamwise and spanwise velocity fluctuations are given in (g) - (i), while (j) - (l) show the corresponding marginal PDF of the streamwise velocity fluctuations at the 3 wall-normal positions.