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Experimental evidence of near-wall reverse flow events in a zero pressure gradient turbulent boundary layer

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ABSTRACT

This study reports on experimentally observed rare near-wall reverse flow events in a fully developed turbulent flat plate boundary layer at zero pressure gradient with Reynolds numbers between $Re_\theta \approx 2500$ and $Re_\theta \approx 8000$ ($Re_\tau \approx 800$–2400). The reverse flow events are captured using high magnification particle image velocimetry sequences with record lengths varying from 50 000 to 126 000 samples. Time resolved particle image sequences allow singular reverse flow events to be followed over several time steps whereas long records of nearly statistically independent samples provide a variety of single snapshots at a higher spatial resolution. The probability of occurrence lies in the order of 0.012–0.018% which matches predictions from direct numerical simulations (DNS). The typical size of the reverse flow bubble is about 30 wall units in length and 5 wall units in height which agrees well with similar observations made in existing DNS data.

1. Introduction

The occurrence of near wall flow reversal and with it the presence of negative values of the local wall shear stress τ_w of turbulent boundary layers (TBL) have been subject of debate over the past decades. Eckelmann [1] postulated that near wall reverse flow was not possible and experimentalists have rarely, if at all, observed this somewhat counter-intuitive flow phenomenon. On the other hand a variety of direct numerical simulations (DNS) suggest the opposite. For DNS of zero pressure gradient turbulent boundary-layers (ZPG TBL) events of negative shear stress have been reported by Spalart and Coleman [2] and also for a turbulent channel flow by Hu et al. [3]. Similar observations have been made by Lenaers et al. [4] using simulations of turbulent channel flow as well as ZPG TBL up to shear Reynolds numbers of $Re_\tau = u_\tau \delta/\nu = 1000$. Negative wall shear stress events are also documented in turbulent pipe flow [5]. Cardesa et al. [6] also confirm the existence of areas of vanishing wall shear stress in DNS of turbulent channel flow at $Re_\tau = 934$ and $Re_\tau = 1834$ and associate these so-called critical points with large scale structures that extend up to 800 wall units downstream. More recently reverse flow events have been characterized through DNS in the adverse pressure gradient (APG) region on the suction side of an airfoil [7].

Common to the observations of the DNS data is that with increasing Reynolds number both the occurrence and the magnitude of the negative axial/streamwise velocities increase. Lenaers et al. [4,7] report reverse flow occurrence of 0.01% for $Re_\tau = 180$ increasing to 0.06% for $Re_\tau = 1000$. In their DNS of fully turbulent channel flow Hu et al. [3] report a probability of negative wall shear ($\tau_w < 0$) of 0.003% at $Re_\tau = 90$ increasing to 0.085% at $Re_\tau = 1440$.

Due to their predicted low occurrence reverse flow phenomena have only been observed rather seldom in experiments involving ZPG wall bounded flows. To properly capture these events long records are necessary which until recently has only been possible for single point techniques, for instance through the use of laser Doppler velocimetry in a ZPG TBL as reported by Johansson [8]. At the same time the employed measurement technique needs to provide adequate spatial

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Table 1
Global parameters of the boundary layer experiments with estimated values given in parenthesis.

Measurement location	X	[m]	3.2	3.2	6.8	6.8
Free stream velocity	U_∞	[m s^{-1}]	5.0	(9.0)	5.0	9.0
Local free stream velocity	U_e	[m s^{-1}]	(5.2)	(9.3)	5.4	9.6
Boundary layer thickness	δ_{99}	[mm]	(59)	(54)	109	102
Displacement thickness	δ^*	[mm]	(10.4)	(9.0)	18.5	16.9
Momentum thickness	θ	[mm]	(7.4)	(6.5)	13.4	12.4
Shape factor	$H_{12} = \delta^*/\theta$		(1.405)	(1.376)	1.381	1.359
Wall shear rate	$\dot{\gamma} = \partial u/\partial y\|_0$	[s]$^{-1}$	2990	8620	2750	8100
Friction velocity	u_τ	[m s^{-1}]	0.213	0.362	0.204	0.350
Friction coefficient	c_f		(0.00333)	(0.00303)	0.00288	0.00262
Pressure gradient	$\partial p/\partial x$	[Pam^{-1}]	−0.17	−0.42	−0.17	−0.42
	$\partial p/\partial x^+$	$\times 10^4$	−2.5	−1.2	−2.5	−1.2
Momentum Reynolds number	$Re_\theta = U_e\theta/\nu$		(2537)	(4000)	4767	7952
Shear Reynolds number	$Re_\tau = u_\tau\delta_{99}/\nu$		(825)	(1293)	1477	2374
Wall unit	$l^* = \nu/u_\tau$	µm	71.3	42.0	74.1	43.2

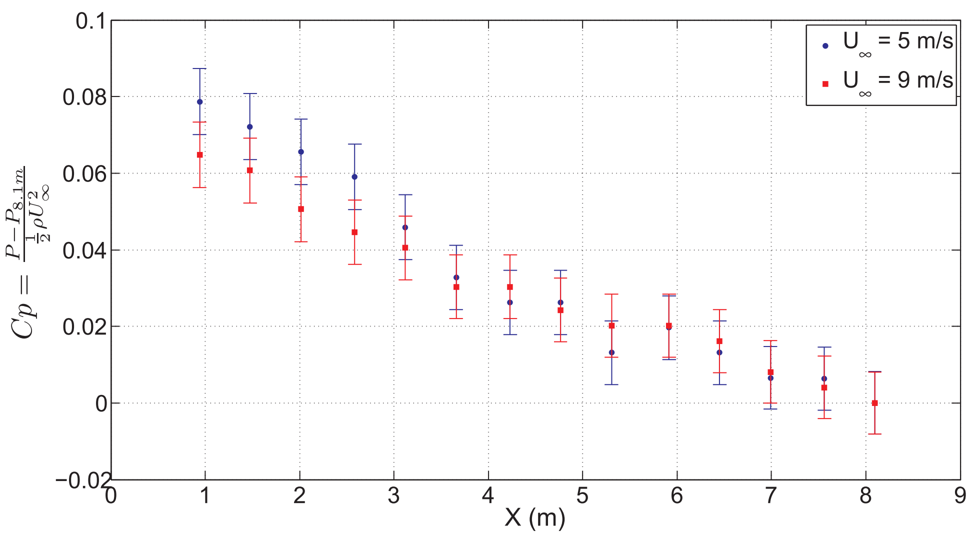

Fig. 1. Streamwise pressure coefficient distribution on the wind tunnel top wall for the two studied free stream velocities with respect to pressure measurement at $X = 8.1$ m.

Table 2
PIV parameters of the boundary layer experiments.

Camera model			PCO Dimax-S4	PCO Edge 5.5
Pixel size		[µm^2]	11.0 × 11.0	6.5 × 6.5
Magnification	m	[µm pixel^{-1}]	25.4	14.1
Image size	$H \times W$	[pixel]	200 × 1008	200 × 2560
Field of view	$w \times h$	[mm^2]	5.08 × 25.6	2.82 × 36.1
Pulse separation	at 5 m/s	[µs]	150	100
	at 9 m/s	[µs]	100	65

resolution as the reverse flow structures observed in DNS data are both short-lived and restricted to the viscous sublayer ($O(5y^+)$). Using the micro pillar shear stress imaging technique, Brücker [9] has recently been able to visualize the areas of reverse flow on a flat plate turbulent boundary layer at $Re_\tau \approx 940$.

Flow topology can nowadays be obtained through particle image velocimetry (PIV), yet, in comparison to single point techniques, PIV is generally restricted in acquisition frequency, number of samples and measurement uncertainty. This can be partially overcome by restricting the camera field of view which allows both an increase of sample rate and sample count [10]. The following reports on PIV measurements in the near wall area of a TBL with a negligible pressure gradient using sample counts exceeding 100 000 which is shown to be sufficient to capture several instance of reverse flow events.

The PIV measurements were primarily conducted to characterize the upstream conditions for a different experiment performed further downstream within the 20 m long test section [11]. Long records, some of which are temporally resolved, enable the capture of rare events such as those described here.

2. Wind tunnel facility

The measurements were performed in the turbulent boundary layer wind tunnel at the Laboratoire de Mécanique de Lille (LML). The measurement positions are located at $X = 3.2$ m and 6.8 m downstream of the boundary layer trip position which is chosen as the origin of the coordinate system with the X-axis aligned in the streamwise direction, Y is the wall-normal and Z the spanwise direction. The tripping device is located at the junction between the contraction nozzle and the 2×1 m^2 rectangular test section and consists of a 4 mm rod attached to the tunnel wall followed by a 93 mm wide strip of coarse sandpaper (roughness 40-grit). Full optical access to the 20 m long rectangular test section is provided by large glass windows on all four sides.

Data was acquired at two free stream velocities of $U_\infty = 5$ m/s and $U_\infty = 9$ m/s with the wind tunnel velocities stable to within 0.5%. Temperature stabilization was set at 20.0 ± 0.1 °C. Table 1 provides the relevant parameters of the turbulent boundary layer at the specific measurement conditions. The friction velocity can be retrieved directly from the PIV measurements using the methodology described in [10]. Other parameters such as the boundary layer thickness are partly estimated from theory (shown in parentheses) since at $X = 3.2$ m only the lower portion of boundary layer was captured by the high resolution PIV measurements. The pressure distribution obtained from discrete positions along the centerline of the tunnel top wall is presented in Fig. 1 and exhibits a small, favorable pressure gradient due to the