Problems of an experimental study of a reverse flow in the turbulent channel flow

D I Zaripov¹,²

¹ School of Mechanical Science and Engineering, Huazhong University of Science and Technology, Wuhan, China
² Kutateladze Institute of Thermophysics, SB RAS, Novosibirsk, Russia

E-mail: zaripov.d.i@gmail.com

Abstract. The problems of experimental study of the near-wall reverse flow (NWRF) phenomenon observed in a turbulent channel flow are discussed. Until now, the problem of detecting the NWRF events has been associated with the lack of spatial resolution of measurement methods. The present study, using the example of high-speed PIV measurements, shows that problems associated with the influence of the measurement error arise even when a high spatial resolution is achieved.

1. Introduction

The near-wall reverse flow (NWRF) phenomenon is characterized by a very small near-wall region with an instantaneous negative value of the streamwise velocity component. On average, this region has the shape of a spheroid flattened in the wall-normal direction [1]. It has been shown in [1,2] that its scales in streamwise, transverse and wall-normal directions do not depend much on the Reynolds number, $Re$, and are about $20x^+$, $20z^+$ and $1y^+$, respectively. It follows that insufficient spatial resolution may be one of the reasons why experimental studies can detect several times lower values of the NWRF occurrence probability or can even completely eliminate it. For example, anticipating the results of experimental studies, a filtering effect of a sensing element of the measuring probe on the experimental results is demonstrated in [1].

There are several other possible problems that complicate correct determination of the statistical and space-time characteristics of the NWRF events. One of such problems is associated with the peculiarity of PIV implementation. In the case of planar PIV, as in the present study, three-dimensional events are sliced by the light sheet. If the sheet slices the event at its edge it becomes smaller, and it is bigger if slicing happens at the symmetry plane of the events.

Another source of the discrepancies in the statistical characteristics of the NWRF events is the way how they are calculated. According to one of them, the largest NWRF event is considered as a spatial extension [1]. Taking into account the fact that these events can be quite large [3], this approach will significantly overestimate the corresponding spatial extensions. In the present study, we adhere to the approach that the space-time extension is equal to the expected value, determined from the analysis of the probability density function (PDF) of the streamwise velocity component.

One more problem is associated with the random measurement errors. For example, one can imagine a situation where experiments show negative streamwise velocity near the wall which is comparable to the random error, i.e. $-u_{rms} < u < 0$. This does not mean that the NWRF event really takes place. Thus, if the appropriate filtering procedure, which eliminates the measurement error and
preserves the real region of the NWRF event, is not applied, one can get a wrong impression about the actual value of the space-time extension of the NWRF region. Thus, a special attention should be paid to the measurement error, especially in the viscous sublayer, where the NWRF events are observed and where the low value of velocity in many cases has an order of the measurement error.

2. Experiments

A fully developed turbulent flow in a 6 m glass channel with square cross-section of \(2H \times 2H = 0.1 \times 0.1 \text{ m}^2\) is considered at Reynolds numbers \(Re = U_b H / \nu = 3100\) and 12400, where \(H\) is the channel half-width, \(U_b\) is the bulk velocity and \(\nu\) is the kinematic viscosity. The corresponding Reynolds numbers, \(Re_s\), based on the friction velocity, \(u_*\), and the boundary layer thickness, \(\delta = H\), are equal to 207 and 672, respectively. Stable air flow rate in the channel is provided by a set of critical flow nozzles mounted between the compressor and the test section of the channel. To provide uniform smoke seeding, the test section inlet is mounted in a smoke conditioning chamber (1.1×1.4×0.65 m\(^3\)). Glycerin particles with the diameter of about 1 µm are used as smoke. Special activities are carried out for a boundary layer closure at a distance of about 2.5 m downstream of the entrance. Measurements are made at a distance of 5 m from the entrance where the turbulent flow is fully developed.

A planar high-speed PIV system is used with the following settings. For \(Re = 3100\) (12400), videos are taken by a high-speed camera Fastec HiSpec 1 with the frame rate of 4000 (3400) fps, resolution of 400×288 (640×240) px and total measurement duration of 447 (221) s. The employed optical system provides for magnification of 60 (135) px/mm. The light sheet is generated by a DPSS laser KLM-532 with adjusted power from 1 to 5 W.

The same processing technique and filtering procedure as in [4] are used, but with the following settings. The images are processed using non-overlapping elongated constant interrogation window (IW) sizes \(l_x \times l_y = 64 \times 8\) px\(^2\) with node-to-node spacing of 64 and 8 px in streamwise and wall-normal directions, respectively. IW sizes correspond to \(l_x^* \times l_y^* = 4.4 \times 0.55\) (6.4×0.8), which are small enough to resolve NWRF region in both directions.

Extreme deviations of velocity vectors from their true values are detected by median test discussed in [5] and replaced by the mean value of neighboring velocities. Additional filtering procedure which significantly reduces the effect of the random error is applied in the present work. Its basics and performance are described in [4]. Its peculiarity is that it enables to exclude the frequency region in which the measurement noise energy dominates over the fluid energy. The following criterion is used to determine the cut-off frequency, \(f_{cut}\):

\[
\frac{|\hat{U}(f_{cut})|^2}{|E|^2} = 2,
\]

where \(\hat{U}(f) = \mathcal{F}[u(t)]\) and \(E(f) = \mathcal{F}[e(t)]\) represent the continuous Fourier transform of measured fluctuating velocity components, \(u\) or \(v\), and random measurement error, \(e\), respectively.

Figure 1 shows distributions of mean streamwise velocity \(U^+\) and turbulent fluctuations \(u' u'^+, \alpha v' v'^+\) along \(y^+\) which are in very good agreement with the corresponding profiles obtained by DNS. A discrepancy in \(\alpha v' v'^+\) profiles for \(y'^+ < 4\) is explained by a measurement error generally resulting from PIV evaluation techniques, which is of the order of 0.1 px in our case. Nevertheless, this low accuracy in wall-normal velocity component in a viscous sublayer will not affect further results and discussions.

3. Results and discussion

Figure 2 represents the difference in the probability of the NWRF occurrence, i.e., the negative value of the streamwise velocity, obtained using raw and filtered oscillograms. It is seen that the NWRF probability is higher inside the NWRF region \((y'^+ \approx 0.3)\) in the case of \(Re = 3100\) and outside it in the case of \(Re = 12400\). This is due to the combined effect of spatial resolution and measurement error.
Figure 1. Wall-normal profiles of (a) mean streamwise velocity and (b) correlations of velocity fluctuations.

According to [4], the measurement error in the case of $Re = 3100$ is higher due to a higher spatial resolution ($l_x \times l_y = 4.4 \times 0.55$). This results in significant, by an order of magnitude, overestimation of the NWRF probability at a distance of $y^+ \approx 0.3$, where the effect of the measurement error is higher. The filtering procedure carried out using criteria (1) allows improving the reliability of determining the NWRF probability in this region. As a result, the number of independent NWRF events decreases from 1163 to 8. A detailed analysis of velocity oscillograms at different distances from the wall shows that all 8 detected events refer to the NWRF phenomenon, while the rest turn out to be random events.

Figure 2. Wall-normal profiles of the NWRF occurrence probability by comparison with similar data obtained by DNS [1].

In the case of $Re = 12400$, application of the filtering procedure does not lead to a significant decrease in the NWRF probability near the wall ($y^+ \approx 0.4$). This is explained by the lower measurement error due to lower spatial resolution [4], i.e., the larger IW size. The number of independent NWRF events detected using raw and filtered data is equal to 119 and 120, respectively. The effect of the measurement error becomes noticeable at a distance from the wall, where the measurement error increases. The presence of reverse flow seen in figure 2 at $y^+ \approx 10$ is, obviously, erroneous. However, the filtering procedure allows slightly reducing this effect.

The profiles presented in figure 2 are used for calculation of the NWRF probability at the wall and mean height of the NWRF region. The corresponding data are shown in figure 3 and compared with the data from the literature. The first parameter is obtained by cubic spline extrapolation of the
profiles, and the second one is calculated from the corresponding PDFs, as mentioned above. Figure 3 shows that if the data near the wall are affected by the measurement error, the NWRF probability can be significantly overestimated in this region \((Re = 3100)\), leading to several times lower value of the mean height of the NWRF region. Moreover, the measurement error included in the data at a distance from the wall \((Re = 12400)\) results in higher NWRF probability and, as a consequence, higher value of the mean height of the NWRF region. If the quantities shown in figure 3 are calculated using the filtered data, their reliability increases fitting, for example, the general trend that the NWRF probability increases with the Reynolds number.

![Figure 3](image)

**Figure 3.** (a) The NWRF probability at the wall and (b) the mean height of the NWRF region by comparison with similar data from the literature for zero-pressure-gradient turbulent boundary layer [6–8] and turbulent channel flow [1, 2, 9–11].

**Conclusions**

The effect of the measurement error on statistics of the near-wall reverse flow (NWRF) phenomenon has been discussed. High-speed PIV measurements have been conducted in a fully developed turbulent flow in the channel with square cross-section at Reynolds numbers \(Re = 3100\) and 12400. It has been shown that the error included in the measured velocity can overestimate the probability of the NWRF occurrence several times even though a high spatial resolution is achieved in experiments. This results in incorrect determination of the mean spatial extension of the NWRF region: it is underestimated and overestimated when the measurement error predominates inside and outside of the NWRF region, respectively. A special filtering procedure, excluding the frequency region in which the measurement noise energy dominates over the fluid energy, reduces the effect of the measurement error and correctly estimates both the probability and spatial extension of the NWRF events.

**Acknowledgments**

This work was supported by the Russian Science Foundation (grant no. 19-79-30075). The computational resources were provided under the state contract with IT SB RAS.

**References**

[1] Lenaers P, Li Q, Brethouwer G, Schlatter P and Örlü R 2012 Phys. Fluids 24 035110
[2] Cardesa J I, Monty J P, Soria J and Chong M S 2019 J. Fluid Mech. 880 R3
[3] Bross M, Fuchs T and Kähler C J 2019 J. Fluid Mech. 873 287–321
[4] Zaripov D, Li R and Dushin N 2019 Fluids 60 18
[5] Westerweel J and Scarano F 2005 Exp. Fluids 39 1096–100
[6] Schlatter P and Örlü R 2010 J. Fluid Mech. 659 116–26
[7] Brücker C 2015 Phys. Fluids 27 031705
[8] Diaz-Daniel C, Laizet S and Vassilicos J C 2017 Phys. Fluids 29 055102
[9] Willert C E, Cuvier C, Foucaut J M, Kliner J, Stanislas M, Laval J P, Srinath S, Soria J, Amili O, Atkinson C, Kähler C J, Scharnowski S, Hain R, Schröder A, Geisler R, Agocs J and Röse A 2018 Exp. Therm. Fluid Sci. 91 320–8
[10] Hu Z, Morfey C L and Sandham N D 2006 AIAA J. 44 1541–9
[11] Jalalabadi R and Sung H J 2018 Phys. Fluids 30 065104