European Journal of Mechanics B/Fluids 55 (2016) 300–312

Contents lists available at ScienceDirect

European Journal of Mechanics B/Fluids

journal homepage: www.elsevier.com/locate/ejmflu

Enhancing the accuracy of measurement techniques in high Reynolds number turbulent boundary layers for more representative comparison to their canonical representations

Ricardo Vinuesa [a,b,*], Hassan M. Nagib [b]

[a] Linné FLOW Centre, KTH Mechanics, Osquars Backe 18, Stockholm, Sweden

[b] Department of Mechanical, Materials and Aerospace Engineering (MMAE), Ilinois Institute of Technology (IIT), Chicago, IL, 60616, USA

ARTICLE INFO

Article history:
Available online 9 October 2015

Keywords:
Canonical flows
Experimental limitations
Turbulence
Hot-wire anemometry
Pitot tubes

ABSTRACT

Existing differences between experimental, computational and theoretical representations of a particular flow do not allow one-to-one comparisons, prevent us from identifying the absolute contributions of the various sources of uncertainty in each approach, and highlight the importance of developing suitable corrections for experimental techniques. In this study we utilize the latest Pitot tube correction schemes to develop a technique which improves on the outcome of hot-wire measurements of mean velocity profiles in ZPG turbulent boundary layers over the range $11\,500 < Re_\theta < 21\,500$. Measurements by Bailey et al. (2013), carried out with probes of diameters ranging from 0.2 to 1.89 mm, supplemented by other data with larger diameters up to 12.82 mm, are used first to develop a somewhat improved Pitot tube correction which is based on viscous, shear and near-wall schemes (which contribute with around 85% of the effect), together with a turbulence scheme which accounts for 15% of the whole correction. The correction proposed here leads to similar agreement with available high-quality datasets in the same Reynolds number range as the one proposed by Bailey et al. (2013), but this is the first time that the contribution of the turbulence scheme is quantified. In addition, four available algorithms to correct wall position in hot-wire measurements are tested, using as benchmark the corrected Pitot tube profiles with artificially simulated probe shifts and blockage effects. We find that the κB-Musker correction developed in this study produces the lowest deviations with respect to the introduced shifts. Unlike other schemes, which are based on a prescribed near-wall region profile description, the κB-Musker is focused on minimizing the deviation with respect to the $\tilde{\kappa}\tilde{B}$ relation, characteristic of wall-bounded turbulent flows. This general approach is able to locate the wall position in probe measurements of the wall-layer profiles with around one half the error of the other available methods. The difficulties encountered during the development of adequate corrections for high-*Re* boundary layer measurements highlight the existing gap between the conditions that can be reproduced and measured in the laboratory and the so-called canonical flows.

1. Introduction

Recent advances in experimental and computational techniques for studying wall-bounded turbulent flows have expanded our knowledge and understanding of many of the physical mechanisms involved [1]. At the same time they have revealed a wide gap between what can be modeled and measured in the laboratory, computed in simulations, and our long-standing idealizations of what we call "canonical flows", i.e., channel, pipe and zero pressure gradient (ZPG) boundary layer. The effects of this gap are manifested not only in the turbulence statistics, but also in the mean flow and the various coefficients defining it [2]. They are also reflected in corner and secondary flows [3,4], inflow conditions [5] and in development length [6] towards the fully developed or equilibrium states in models of the canonical flows.

In the present study we focus on the physical limitations encountered by experimentalists when measuring the canonical ZPG boundary layer at high Reynolds numbers. Experimental studies on fundamental research of wall-bounded turbulence require very careful assessment of the experimental procedures, and the

* Corresponding author at: Linné FLOW Centre, KTH Mechanics, Osquars Backe 18, Stockholm, Sweden.
E-mail address: rvinuesa@mech.kth.se (R. Vinuesa).

http://dx.doi.org/10.1016/j.euromechflu.2015.09.004

highest possible accuracy, in order to provide reliable data for adequate interpretation, validation of theories, etc. A wide range of measurement techniques are available for turbulent flow measurements, including Particle Image Velocimetry (PIV) or the more recent multi-plane PIV [7], which are able to reproduce the velocity field in localized regions of the flow, or the more traditional Pitot tube and hot-wire probes which allow us to measure the mean flow and (in the case of hot-wires) one or more components of the Reynolds stress tensor. In addition to reliable mean velocity measurements, accurate determination of wall shear stress is also crucial for fundamental research on wall-bounded turbulence, especially for scaling and asymptotic theory considerations [8]. On this topic, advancements in the Oil Film Interferometry technique (OFI), which is based on the analysis of the motion of a thin oil film driven by the turbulent stream to determine local wall-shear stress accurately, have been essential to improve its accuracy from 5% 20 years ago [9] to somewhere between 0.5% and 1% in the past decade [10,11,6]. In this context, [12] have recently published a review on experimental procedures to be used with Pitot tubes, which also contains comparisons between Pitot tube and hot-wire measurements. They present a comprehensive database of Zero Pressure Gradient (ZPG) Turbulent Boundary Layer (TBL) measurements taken at the MTL wind tunnel from the Royal Institute of Technology (KTH) [13], the HRNBLWT at the University of Melbourne [14] and the NDF at the Illinois Institute of Technology (IIT) [8], carried out as a part of ICET (International Collaboration on Experimental Turbulence), an international campaign for turbulent measurements started in 2008. We will use their published information as part of the database here, because of our intimate familiarity with and access to these datasets as coauthors of [12].

Measurements suffer from various sources of error that need to be accounted for by means of corrections in order to obtain accurate and reliable results. Since it is not possible to obtain one-to-one comparisons of experimental, computational and theoretical representations of the flow (due to the gap mentioned above), we cannot pinpoint the absolute contributions of the various sources of uncertainty on each approach. For example, computations rely on various schemes to account for streamwise non homogeneity and layer growth, and several approximations and assumptions are embedded in any theoretical description of the flow. It is therefore important to keep in mind the various limitations of the three areas in order to evaluate how reliable a particular comparison is. In this study we aim at improving the accuracy of hot-wire anemometry, particularly in the near-wall region of high Reynolds number turbulent boundary layers. These measurements suffer from several problems, such as heat conduction to the walls, natural convection effects, and also inaccuracy in probe position (as described by [15]). This last effect turns out to have an important impact on experimental measurements with hot-wires, significantly compromising the accuracy of the results when combined with blockage effects of the wire supports, tilting or bending of the traverse, or even slippage in the traverse mechanism. In fact, [16] argue that errors in the position of the first point may contribute with up to 90% of the total error in estimating integral quantities in ZPG boundary layers. Pitot tubes do not have this problem, since one can start the measurements with the probe in contact with the wall, which is not the case for hot-wires due to the mentioned heat transfer to the wall problems, and risk of breaking the wires. The accuracy of different existing algorithms aimed at correcting the probe position in hot-wire measurements is assessed in Section 4 by means of the following procedure: random errors are artificially introduced into the fully corrected Pitot tube profiles and their magnitudes tracked. The different algorithms are then used to try to recover the original profiles, thus evaluating their accuracy. In addition, we also compare the Pitot data with hot-wire measurements taken as part of the same experimental campaign in order to show how good the agreement between the various correction schemes is.

In view of the importance of the accuracy in the Pitot-tube profiles we use here as a benchmark or reference, we start by revisiting the experimental procedures and corrections for measurements in high Reynolds number turbulent boundary layers currently available in the literature for Pitot tubes. The latest knowledge on experimental work with Pitot tubes indicates that it is necessary to apply, among others, a near-wall correction (introduced by [17]), a shear correction (a widely used form was proposed by [18]), and [12] indicated that a correction for turbulence effects may be necessary too. These corrections are briefly reviewed in Section 2, and new functional forms (including an updated version of the turbulence correction) are also described. We also discuss the accuracy of the new functional forms and the effect of the various corrections on the data presented in [12].

2. Pitot tube corrections revisited

The mean flow profiles obtained by [12] are analyzed in this section. In order to assess the quality of the profiles, comparisons are carried out with an extensive database of available high-quality ZPG data compiled by [19], and exhaustively reanalyzed in a consistent way during this study. Fig. 1 (top) shows three $\Delta U^+ = U^+_{\text{ensemble,Pitot}} - U^+_{\text{ensemble,hot-wire}}$ profiles plotted in a logarithmic scale of y^+. Here '+' denotes inner scaling, with $u_\tau = \sqrt{\tau_w/\rho}$ (where τ_w is the wall shear stress and ρ is the fluid density) and $\ell^* = \nu/u_\tau$ (ν being the fluid kinematic viscosity) as velocity and length scales respectively. Each $U^+_{\text{ensemble,Pitot}}$ profile is obtained as an interpolated ensemble average of 4 Pitot profiles, 2 measured in the MTL wind tunnel at KTH (with Pitot diameters 0.2 and 0.3 mm) and 2 measured in the HRNBLWT at Univ. of Melbourne (with $d_p = 0.3$ and 0.51 mm). The three ensemble curves correspond to velocity profiles at Reynolds numbers based on momentum thickness θ of $Re_\theta \simeq 11\,500$, $16\,000$ and $21\,500$. With respect to the $U^+_{\text{ensemble,hot-wire}}$, each of them was obtained as interpolated ensemble average of a number of hot-wire profiles with the same Reynolds numbers from [19]. The results shown in Fig. 1 (top) reflect that the series of corrections proposed by [12] *including the turbulence correction* exhibit better agreement than the corrections based on the Modified McKeon *without turbulence correction*, also suggested by [12]. In fact, the agreement between the turbulence-corrected Pitot profiles and the hot-wire data for $y^+ > 200$ is really good, as opposed to the Modified McKeon alternative which only shows good agreement beyond $y^+ = 1000$. Below $y^+ = 200$, the turbulence-corrected profiles exhibit a U^+ discrepancy of around 0.1 between $y^+ = 30$ and 40, whereas this disagreement is between 0.3 and 0.4 in the case of the Mod. McKeon approach.

Fig. 1 (bottom) shows that the differences around y^+ of 30–40 result in a disagreement between the von Kármán coefficient κ (determined using the composite fit by [19]) extracted from the Pitot tube profiles and the average value determined using the hot-wire data ($\kappa = 0.384$). The average κ from the turbulence-corrected profiles is 0.389, whereas the one from the Mod. McKeon data is as large as 0.398. Similar disagreement, but with slightly different values, is also found when using any of the standard schemes to extract κ values from the profiles [2]. The differences with respect to hot-wires are important, which is surprising since turbulence-corrected Pitot and hot-wire data exhibit very good agreement for almost the entire extent of the boundary layer. However, the disagreement in the range y^+ of 30–40, which is in the buffer region and is essential for the adequate transition to the logarithmic overlap layer, plays an important role in this discrepancy. These results motivated the re-evaluation of the Pitot tube corrections proposed by [12]. In addition to the Pitot-tube data used by [12], we included in the following re-evaluation data with Pitot tubes of diameters ranging up to 12.82 mm used in the NDF with boundary layers of comparable Reynolds numbers