Experimental Thermal and Fluid Science 40 (2012) 140–149

Contents lists available at SciVerse ScienceDirect

Experimental Thermal and Fluid Science

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

Turbulence profiles from a smooth flat-plate turbulent boundary layer at high Reynolds number

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ARTICLE INFO

Article history:
Received 13 December 2011
Received in revised form 20 February 2012
Accepted 20 February 2012
Available online 3 March 2012

Keywords:
Turbulence
Boundary layer
High Reynolds number
Measurements

ABSTRACT

Much is known about smooth-flat-plate turbulent boundary layers (TBLs) at laboratory-scale Reynolds numbers because of a wealth of experimental data. However, smooth-flat-plate TBL data are much less common at the high Reynolds numbers typical of aerodynamic and hydrodynamic applications ($Re_x \sim 10^8$–10^{10}), and at the even higher Reynolds numbers of many geophysical flows. This paper presents new LDV-measured profiles of the stream-wise velocity variance, the wall-normal velocity variance, and the Reynolds shear stress from the TBL that formed on a smooth flat plate at Karman numbers from 15,000 to 60,000 (Re_x from 75 million to 220 million). The experiments were conducted in the William B. Morgan Large Cavitation Channel on a polished ($k^+ < 0.2$) flat-plate test model 12.9 m long and 3.05 m wide at water flow speeds up to 20 m s^{-1}. The TBL on the model developed in a mild favorable pressure gradient having an acceleration parameter $K \sim 10^{-10}$. When plotted with the usual inner and outer scalings, the stream-wise velocity variance profiles display a Reynolds number dependence that is consistent with prior lower Reynolds-number zero-pressure-gradient TBL measurements. However, using the same normalizations, the profiles of wall-normal velocity variance and Reynolds shear stress are found to be Reynolds number independent, or nearly so, when experimental uncertainties are considered.

1. Introduction

After nearly a century of investigation, the structure and scaling of turbulent boundary layers (TBLs) at high Reynolds number remains an active research area [1]. The published literature on TBLs is extensive, and review articles [1–6] and recent texts [7,8] provide fine summaries of this material along with listings of current and recurring issues. One recurring issue arises from the great abundance of experimental studies involving laboratory-scale flat-plate TBLs when compared to the prevalence of equivalent measurements at the larger scales typical of aerodynamic and hydrodynamic applications, and of atmospheric and oceanic flows. In laboratory-scale TBL flows the nominal downstream-distance-based Reynolds number, Re_x, is typically less than 10^7 or so, while for passenger airliners and commercial ships Re_x may reach 10^9 or 10^{10}.

Because of the lack of experimental data from controlled tests at high Reynolds number, the scaling procedures necessary to relate laboratory-scale TBL results to full-scale aerodynamic and hydrodynamic applications, and to geophysical TBL flows are not fully identified. For years it was believed that the scaling found in laboratory-scale flows would persist at much higher Reynolds numbers. However, the expanded range of turbulent length scales at high Reynolds number, and the interaction of near-wall structures with large-scale and very-large-scale structures leads to Reynolds number dependence in TBL flows [9,10] that cannot be deduced from low- and moderate-Reynolds-number TBL experiments alone. Therefore, to further develop and refine TBL scaling procedures, new high-Reynolds number data are needed [6]. This paper addresses this need by presenting results from a high-Reynolds number experimental study of the TBL that formed on a smooth flat plate in a mild favorable pressure gradient. The Karman numbers of this study, $\delta^+ = u_\tau\delta/\nu$, ranged from 15,000 to 60,000 ($Re_x = U_e x/\nu$ from 75 to 220 million) while Launder's acceleration parameter, K, varied from 4×10^{-10} to 1×10^{-10}. Here, the usual parameter definitions apply: $u_\tau = \sqrt{\tau_w/\rho}$ is the shear velocity, ρ is the fluid density, τ_w is the local mean wall shear stress, δ is the boundary layer thickness determined from the wall-normal extent of the turbulence profiles, ν is the fluid's kinematic viscosity, U_e is the free-stream fluid velocity at the upper edge of the boundary layer, and x is the stream-wise coordinate with $x = 0$ at the test model's leading edge.

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0894-1777/$ - see front matter
doi:10.1016/j.expthermflusci.2012.02.009

In general, the correct Reynolds-number scaling of the mean flow and turbulence quantities in a TBL is of practical and scientific interest. The companion study [11] to the current manuscript reports such scaling results from the same high-Reynolds number experiments for the mean stream-wise velocity profile $U(y)$, where y is the wall-normal coordinate. Thus, the purpose of this paper is to concisely report results for the profiles of the stream-wise velocity variance $\overline{u'^2}$, the wall-normal velocity variance $\overline{v'^2}$, and the Reynolds shear stress $-\rho\overline{u'v'}$, where a prime denotes a fluctuation, and the overbar denotes a time or ensemble average. For consistency with the copious prior TBL literature, profiles of these turbulence quantities are plotted using the standard notation and law-of-the-wall or outer normalizations. Velocities are scaled by the shear velocity u_τ. Wall-normal distances are scaled with the viscous length scale (or wall unit) $l_\nu = \nu/u_\tau$, or with δ. And, a superscript '+' is used to denote quantities rendered dimensionless with u_τ and l_ν. Thus, the Karman number δ^+ can be written δ/l_ν. In addition, for conciseness (and clarity), detailed tests and comparisons covering the many new TBL scaling ideas that have been proposed in recent years are not attempted. Yet, to facilitate such comparisons, the measured profile data are tabulated in dimensional form in the Appendix. The main findings reported here are that the current turbulence profile results are consistent – within experimental uncertainty – with prior trends suggesting that the magnitude of $\overline{u'^2}^+$ retains a Reynolds-number dependence while the magnitudes of $\overline{v'^2}^+$ and $-\overline{u'v'}^+$ are (at most) weakly dependent and independent, respectively, of changes in Reynolds number.

The remainder of this paper is divided into three sections. The next one succinctly describes the experimental setup. The third section presents the TBL turbulence profile results. The final section summaries this study and states the conclusions drawn from it.

2. Description of the experiments

The experiments are described in detail in [11], so this and the following paragraphs provide a concise summary of the setup and experimental techniques. The experiments were conducted in world's largest low-turbulence water tunnel, the US Navy's William B. Morgan Large Cavitation Channel (LCC) [12] at nominal flow speeds of 6.7, 13, and 20 m s^{-1} leading to l_ν between 4.7 an 1.7 μm, and δ between 115 and 69 mm. At these speeds, the LCC's test-section centerline turbulence level was 0.2–0.4%. Over the multi-week duration of the experiments water temperature varied between 18 °C and 30 °C with an average of 21.2 °C. Thus, the average water density and kinematic viscosity were ρ = 998 kg m^{-3}, and $\nu = 9.75 \times 10^{-7}$ m^2 s^{-1}, respectively, and these values were used for data reduction and in the various normalizations. During the tests, thermal variations may have lead to 10% changes in water kinematic viscosity.

The test model was an effectively-rigid flat plate with an elliptical nose and a tapered trailing edge having an overall length, width, and thickness of 12.9 m, 3.05 m, and 18.4 cm. Vibration velocities deduced from accelerometers mounted inside the model were an order of magnitude smaller than the velocity resolution of the LDV system and were also well below the LCC's free-stream velocity fluctuation level. This is the largest possible flat-plate model that could fit the parallel-wall portion of the LCC's test section. The model's test-section blockage was ~6% and this lead to a free-stream flow speed, U_e, as high as 20.2 m s^{-1} at the edge of the developing boundary layer. A schematic of the model and the laboratory coordinate system are shown in Fig. 1. The test surface was polished 304 stainless steel with a nominal surface roughness of 0.4 μm, except for a distributed-roughness trip located between x = 25 mm and x = 250 mm that was composed of nominally 120-μm-diameter sand grains (100 grit) embedded in a film of epoxy and spaced randomly 2–5 mm apart. The ratio $k^+ = k/l_\nu$ was less than or equal to 0.2 over the test surface for all flow conditions. Except for the injector opening at x = 1.32 m, the test surface downstream of the trip was hydraulically smooth. A cross section of the injector is shown in Fig. 2 and it was used to inject polymer solutions in skin-friction drag-reduction experiments [13]. A variety of skin-friction drag reduction experiments were conducted with this test model and are reported elsewhere [13–16].

Static pressure P was measured at 11 downstream locations along the length of the model at y = 48.3 cm on a sidewall of the LCC. The pressure coefficient, $C_P(x) = (P(x) - P_1)/\frac{1}{2}\rho U_e^2$, where P_1 in the pressure measured at the first tap at x = 1.96 m, computed from these measurements declined linearly from the first tap location to -0.040 ± 0.003 at x = 10.8 m, the furthest downstream measurement location. Thus, the TBL on the test surface developed in a mild favorable pressure gradient. The increase in free stream speed over the test surface was ~2.5%, consistent with TBL growth on the test surface and the interior walls of the LCC test section. In terms

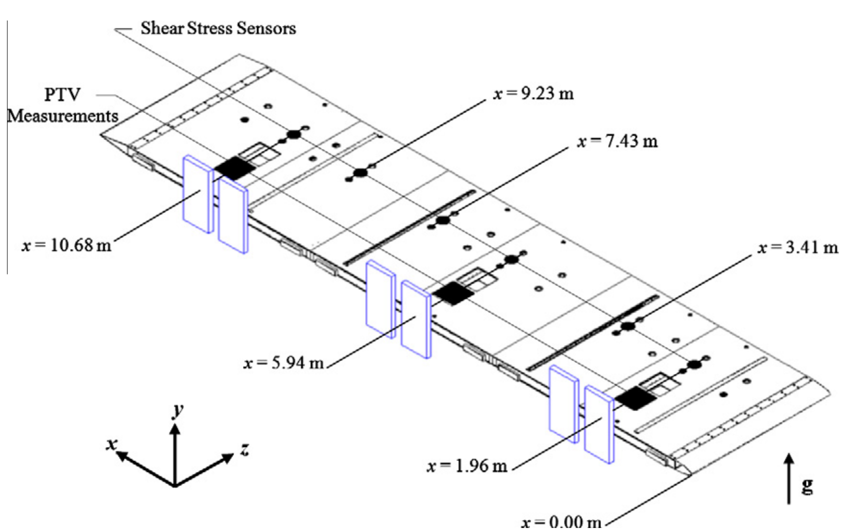

Fig. 1. Schematic of the model with the experimental coordinate system. The four-to-one elliptical leading edge lies at x = 0, and the test surface coincides with y = 0. LDV profile measurements were made in double columns nominally centered at x = 5.94 m, and 10.68 m. For the experiments described here, the model was inverted so the direction of gravitational acceleration is inverted.