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An experimental study of turbulent boundary layers approaching separation

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ABSTRACT

The present paper deals with the experimental analysis of a strong decelerated turbulent boundary layer developed on a flat plate. The aim of the study was to examine the effects of pressure gradient on a non-equilibrium boundary layer while indicating local areas of equilibrium flow. The effect of the Reynolds number on a turbulent boundary layer developed with matching the external pressure gradient conditions was also analysed. The emphasis was on the analysis of mean flow statistics i.e. mean velocity profiles, streamwise Reynolds stress and the effect of large- and small-scale interactions by analysing the skewness factor and energy isocontours maps. The comparative analysis of the external data indicated that the structure of the turbulent boundary layer depends not only on local effects of pressure gradient but also on the upstream history of the flow. For the same condition of pressure gradient, the increased momentum is observed near the wall with the increase of the Reynolds number at the Incipient Detachment, where increased turbulence production is also observed, leading to the failure of the outer scaling methods. Surprisingly, the effect of the Reynolds number decays at the intermittent transitory detachment where similar profiles were observed. The upper inflection point in the mean profile corresponded well with the outer maximum of the Reynolds stress and zero crossing of skewness factor. Position of this point occurs at different locations, depending on the flow history effects. The last observation demonstrates that the inflection points results from large- and small-scale interactions, which led to the increased convection velocity of small scales near the wall.

1. Introduction

Most flows of practical interest are turbulent and hence understanding of these flows is important for both engineering and fundamental reasons. It is however clear that turbulence remains one of the most important unsolved problems of classical physics. The problem is especially evident for wall-bounded flows, which consist of a wide range of three-dimensional motions, from large and slow to small and fast structures. Among various types of near-wall flows, a significant amount of research has been devoted to understanding canonical flat plate zero pressure gradient turbulent boundary layers (TBLs) (Alfredsson et al., 2011; Marusic et al., 2010; Nagib et al., 2007; Smits et al., 2011). However, the TBLs subjected to a streamwise adverse pressure gradient (APG) are nowadays in the spotlight because they are frequently encountered in many engineering applications, such as diffusers, compressor and turbine blades, and the trailing edges of airfoils. The performance of such flow devices is significantly affected by the presence of the adverse pressure gradient.

If a turbulent boundary layer flow encounters a strong APG, the flow becomes unstable and it separates from the surface. A characteristic feature of turbulent separation is an unstable location in time and space. An extensive phenomenological description of the flow separation distinguishing various stages of separation was given by Simpson (1989). He shown that downstream the incipient separation (1% instantaneous back flow), these large-scale structures grow rapidly and agglomerate with one another. It is also the region where the displacement thickness of the boundary layer begins to increase significantly. The unstable location of turbulent separation results from the impact of the vortical structures that fall into the area of separation, causing a temporary increase in momentum (Cherry et al., 1984). Buckles et al. (1984) showed that in the flow separation, the vortices send fluid towards the wall (sweep event) and entrain fluid from the reversed-flow region upward (increase of momentum). This is correlated with large, positive streamwise velocity skewness values in the reversed-flow region caused by the passage of shear-layer vortices overhead. Based on the above description, it can be stated that the vortical structures deliver a momentum near the wall. These observations led Buckles et al. (1984) to suggest that the detached shear flow was driven by a mechanism other than just the external pressure gradient. Furthermore, Maciel et al. (2006) pointed out that “pressure force and the turbulent transport no longer play an important dynamic role close to separation … TBL has therefore become essentially an

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inertial flow zone where equilibrium is likely to occur”. Up to now the strong inertia effect was linked only to separation on the bluff body edges, where the separated flow creates large swirl motion driven by shading vortices presented among others by Gnatowska (2008). The turbulent boundary layer that is maintained on the verge of separation has already been studied numerically and experimentally (e.g. Elsberry et al., 2000; Krogstad and Skare, 1995; Skote and Henningson, 1998). Krogstad and Skare claim, using classical Clauser concept, that the flow close to separation exhibits a definite non-equilibrium character, indicated by the different scales required for the collapse of the mean velocity and turbulence intensity profiles. Castillo et al., (2004) used boundary layers equilibrium similarity and pressure gradient Λ parameter and showed that the outer part of a turbulent boundary layer under strong adverse pressure gradient and even near and past the separation, tends to remain in the equilibrium state. Analysis of the separated boundary layer cannot be performed in isolation from the study of APG TBLs flows. Recent research papers on this issue concern scaling and statistics analysis of non-equilibrium boundary layers: Dróżdż et al. (2015); Gungor et al. (2016) in equilibrium; Monty et al. (2011); Kitsios et al., (2016) or near-equilibrium Bobke et al., (2017). As shown recently by Bobke et al., (2017), the scaling problem with pressure gradient flows emerges from different history upstream flow effects. These researches showed that comparison of the flows with different conditions of flow history at the same value of Clauser–Rotta pressure gradient parameter β, defined as: $\beta = \frac{\delta^*}{\tau_w}\frac{dP_\infty}{dx}$, does not guarantee the collapse of the mean or Reynolds stress profiles even for the same Reynolds number.

The deep analysis of the flow structure was performed by Marquillie et al. (2011), where correlation between a streak bursting process and the increase in outer large-scale motion energy was demonstrated. The same problem was addressed in the paper by Maciel et al. (2017a), where the turbulent quadrant events modifications in APG were shown. Harun et al. (2012) and Lee (2017) identified the large-scale amplitude modulation of near-wall turbulence phenomenon, while Dróżdż and Elsner (2017b) have shown the relationship between amplitude modulation phemomenon and convection velocity of turbulence. The large- and small-scale interaction, which was elucidated on filtered velocity small- and large-scale signals for ZPG (Mathis et al., 2011) and APG (Dróżdż and Elsner, 2017a; Harun et al., 2013) flows. In the latter case, the study concerned weak pressure gradients (Dróżdż and Elsner, 2017a; Harun et al., 2013). The physical background of amplitude modulation phenomenon remains unclear (Jacobi and McKeon, 2013). It has recently been shown that it influences the convection velocity of the near-wall small-scale structures and that the convection velocity varies near the wall depending on the pressure gradient (Dróżdż and Elsner, 2017a). The effect of convection velocity modulation by large-scale motions was also recently discussed by Baars et al. (2017). Dróżdż and Elsner (2017b) showed using a two point correlation for the flows with strong APG ($\beta = 17$) that convection velocity surpasses the mean velocity two times on average in the buffer layer. It follows that the increased convection velocity can play an important role in wall-normal momentum transport for the strong pressure gradient near detachment and especially for higher Reynolds number flows. For low Reynolds numbers and medium β i.e. below 5, its role is insignificant but it is not the case for more destabilized TBLs. Therefore, there is a strong need for the analysis of TBLs near separation in the aspect of large- and small-scale interactions.

The most of available experimental studies with APG flows fail to present canonical setup and well-documented data sets near boundary layer detachment. The paper attempts to fill this gap, and investigates both APG and Reynolds number effects. The main motivation of the present study is to address the similarity problem of such flows and the role, in this aspect, of upstream history effect. It was also attempted to assess the importance of the phenomenon of large- and small-scale interactions known as amplitude modulation near boundary layer detachment and the impact of this phenomenon on flow statistics.

2. Experimental facility and measurement technique

The experiment was performed in an open-circuit wind tunnel, where the turbulent boundary layer was developed along the flat plate, which was 6870 mm long. The wind tunnel was designed with large dimension settling chamber and three contraction sections in order to achieve free stream turbulence intensity of below 0.7% at the inlet plane ($x = 0$ mm). Tripping of the boundary layer after the leading edge was used to bypass laminar-turbulent transition. For this purpose, a strip of coarse-grained sandpaper ranging from 60 to 250 mm from the flat plate leading edge was used. The inlet rectangular channel with a length of 5035 mm located upstream the proper test section has two pairs of suction gaps aimed, at maintaining overpressure, to control the two-dimensionality of the flow by minimizing the boundary layers on the side walls. Triangular corner inserts were used in the whole inlet channel to reduce the effect of secondary vortices developing along rectangular channel. A slight inclination of the upper wall helped maintain zero pressure gradient ($\frac{dP_\infty}{dx} \approx 0$, where P_∞ is external static pressure and x is the streamwise direction) conditions at the inlet.

The specially design test section located at the end of the wind-tunnel (see Fig. 1) is equipped with a perforated, movable upper wall. Wall perforation of 10.1% was adopted, characterized by 0.5 mm circular holes. Computer-controlled suction system equipped with a low power axial compressor allows for smooth adjustment of the amount of the air exhausted from the top of the wall. Modification of the shape and position of the upper wall and the suction flux allows for generation of a wide range of pressure gradient conditions, while the zero pressure gradient conditions were maintained at the inlet channel. With specific pressure conditions, it is possible to generate, on the bottom wall, a turbulent boundary layer which is at the verge of separation. Full separation on the lower flat plate does not occur even for the suction case. After that point, due to the cessation of suction, the flow returns to the attached state. The overpressure guarantees that there is no reverse flow in the outlet plane, which was spaced from the last measurement plane by 435 mm.

The facility is equipped with the computer-controlled 2D traversing system (1500 mm in the streamwise direction and 180 mm in the wall-normal direction). Uncertainty of the drive step in the wall normal direction was 0.001 mm, with the smallest step of 0.01 mm, while in the streamwise direction this value was 0.04 mm for the smallest step of 0.375 mm.

The velocity measurements were performed with hot-wire anemometry CCC developed by the Polish Academy of Science in Krakow. A single hot-wire probe of a diameter $d = 3\,\mu$m and length $l = 0.4$ mm was used. During the experiment the non-dimensional wire length ($l^+ = lu_\tau/\nu$, where u_τ is friction velocity $u_\tau = \sqrt{\frac{\tau_w}{\rho}}$, $\tau_w = \mu\frac{dU}{dy}$ is wall

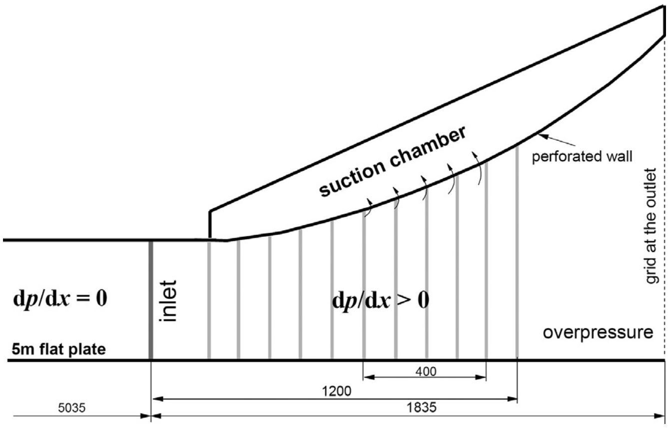

Fig. 1. Test section geometry.