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Scaling and statistics of large-defect adverse pressure gradient turbulent boundary layers

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ABSTRACT

The purpose of this article is to test similarity laws and scaling ideas, as well as characterize turbulence behaviour of large-defect adverse-pressure gradient turbulent boundary layers using six experimental and numerical databases including a new direct numerical simulation of a strongly decelerated non-equilibrium turbulent boundary layer. In the latter flow, at a moderate Reynolds number, the mean velocity profiles depart from the classical law of the wall throughout the inner region including in the viscous sublayer and they do not follow the log law. However, the agreement is excellent with the extended law of the wall that accounts for the pressure gradient for the viscous sublayer. The Reynolds stress components are not self-similar in the viscous sublayer when the velocity defect is important, but they scale reasonably well with the pressure-viscous scales.

Detailed comparisons of the six different flows are made in the outer region. In order to do such comparisons, an outer region velocity scale analogous to the commonly defined free shear layer velocity scales is introduced. It is found that the investigated one-point velocity statistics in the upper half of large-defect boundary layers resemble those of a mixing layer: mean velocity defect, Reynolds stresses, turbulent kinetic energy budgets, uv correlation factor and structure parameter $-\langle uv\rangle/2k$. The dominant peaks of turbulence production and Reynolds stresses are located roughly in the middle of the boundary layer. The profiles of the uv correlation factor reveal that u and v become less correlated throughout the boundary layer as the mean velocity defect increases, especially near the wall. The structure parameter is low in the large-defect disequilibrium boundary layers, similar to large-defect equilibrium flows and mixing layers and decreases as the mean velocity defect increases. All large-velocity-defect boundary layers analysed are found to be less efficient in extracting turbulent energy from the mean flow than zero-pressure-gradient turbulent boundary layers, even throughout the outer region.

1. Introduction

Wall-bounded turbulent flows are important to understand in order to improve energy efficiency for a wide range of machines and systems associated with these turbulent flows. An important sub-group of wall bounded turbulent flows are adverse pressure gradient (APG) turbulent boundary layer (TBL) flows. These flows are found for instance around surfaces with curvature, as encountered in many aerodynamic applications such as airplane wings, cars and turbomachinery. Although a significant amount of research has been devoted to understanding channel flows, pipe flows and zero pressure gradient (ZPG) turbulent boundary layer flows, which has led to a consistent theory of these canonical wall flows, the same cannot be said for APG TBLs. There exists nonetheless a wealth of theoretical, experimental and numerical studies on APG TBLs, many of which are summarized below. Among many things, these studies clearly demonstrate that the fundamental problem in APG boundary layer flow research is the lack of a recognized theoretical framework and, consequently, a lack of well-thought laboratory and numerical experiments based on such a framework. A clear and agreed understanding of which parameters are paramount for the development of the APG boundary layer does not yet exist. An overview will be presented of the most significant ideas and results which are consequential to the study reported in this article.

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The velocity components of the boundary layer flow are denoted by u, v, w in the respective spatial coordinates x, y, z for the streamwise, wall-normal and spanwise directions, respectively. For the sake of the discussion and to retain generality, the length and velocity scales of the inner and outer regions of the boundary layer are left unspecified for the moment and are denoted respectively as L_i, U_i and L_o, U_o. We will limit the discussion to two regions because we can neither confirm nor refute that a third, intermediate region may exist for some categories of APG TBLs; the layer-structure and scaling of the TBL is discussed further on.

In addition to the presence and sign of the pressure gradient, pressure gradient TBLs can be further distinguished with two important characteristics of shear layers: (1) the importance of the mean velocity (momentum) defect and (2) the state of dynamic equilibrium. The mean velocity defect, $U_e - U(y)$, where U_e is the external velocity at the edge of the boundary layer, reflects the local state of the boundary layer as a consequence of the upstream history of the flow. It gives an indication on the strength and distribution of mean shear rates and hence partly also on the local characteristics of momentum transfer and turbulence behaviour. In that respect, large-velocity-defect TBLs resulting from a strong or a prolonged adverse pressure gradient are quite distinct from ZPG TBLs and small-defect APG TBLs. In their case, mean shear rates in the outer region are no longer small in comparison to their near-wall counterparts while near the wall, the importance of viscous forces and of the wall shear stress diminishes. As a result, the near-wall turbulent kinetic energy production peak is absent or very small and the main production peak is found in the outer region of the flow (Elsberry et al., 2000; Na and Moin, 1998; Skåre and Krogstad, 1994). In the case of very large defect boundary layers, for instance near separation, turbulence activity is almost absent near the wall (Elsberry et al., 2000; Maciel et al., 2006b; Na and Moin, 1998; Skåre and Krogstad, 1994; Skote and Henningson, 2002) essentially because mean shear is negligible there. The shape factor $H = \delta^*/\theta$, where δ^* and θ are the displacement and momentum thicknesses respectively, and Clauser shape factor (Clauser, 1954), that is based on similarity theory and that is not as dependent on Reynolds number, are possible indicators of the importance of the mean velocity (momentum) defect.

The other important characteristic is the state of dynamic equilibrium of the boundary layer. Most real TBLs are complex because under the influence of external factors such as the pressure gradient they depart from dynamic equilibrium, in the sense that there exists a streamwise variation of the relative importance of each force acting on the flow, e.g. inertia, pressure and viscous forces. In the traditional theory of equilibrium TBLs (Clauser, 1954; Rotta, 1950), the friction velocity $u_\tau = \sqrt{\tau_w/\rho}$, where τ_w is the wall shear stress and ρ is the density, is implicitly assumed to be the outer velocity scale. Maciel et al. (2006a) have recast the theory in more general terms by avoiding the assumption of *a priori* outer scales. They showed that the main parameter that characterizes the impact of the pressure gradient on the outer region of all types of PG TBLs is a generalized form of the Rotta–Clauser's pressure gradient parameter

$$\beta_o = -\frac{L_o}{U_o}\frac{dU_e}{dx}. \tag{1}$$

This assumes that appropriate outer scales can be found to represent all types of TBLs (see discussion on scales below). A pressure gradient parameter also needs to be defined for the near-wall region as will be done subsequently, but it suffices for the moment to discuss the outer one. If the pressure gradient parameter β_o remains constant, then the TBL is in equilibrium or quasi-equilibrium in its outer region (equilibrium is not necessarily complete because at finite Reynolds number, a constant β_o is not the only condition necessary for similarity as described in Maciel et al., 2006a). In the case of non-equilibrium TBLs, an increase (decrease) in β_o leads to an increase (decrease) of the mean velocity defect. Large velocity defect and boundary layer separation can therefore be due to a sharp streamwise positive gradient of β_o, even if they occur downstream in a region where $d\beta_o/dx$ is no longer positive, or from a prolonged mild positive $d\beta_o/dx$.

Besides studies on equilibrium TBLs, such as Clauser (1954), Stratford (1959), East and Sawyer (1980), Skåre and Krogstad (1994), and Lee and Sung (2009), there have been many studies in the past of TBLs subjected to favourable or adverse pressure gradients that lead to non-equilibrium conditions, reviewed for instance in Skote and Henningson (2002) and Maciel et al. (2006b). In most of these studies, the pressure distribution was chosen rather arbitrarily from a theoretical viewpoint, often with a specific practical application in mind. It therefore resulted in random and sometimes complex streamwise evolutions of β_o whatever the assumed outer scales (Maciel et al., 2006a). It is not often recognized that the state of the boundary layer is directly attributable to the streamwise variation of β_o (and β_i) and not simply to the presence of a pressure gradient. As a result, even if we have an overall knowledge of the main effects of the pressure gradient on TBLs, we do not fully understand them. Moreover, we are still unable to make a clear distinction between the local effects of pressure gradient and those resulting from the upstream history on the non-equilibrium evolution of a TBL.

It is also important to discuss the mean flow structure, the various similarity laws and the scaling of TBLs subjected to pressure gradients since there exist several interpretations and theories. In the case of canonical wall-bounded turbulent flows and small-defect TBLs, a two-region structure (inner/outer) further subdivided into four layers (viscous sublayer, buffer layer, overlap layer and defect layer) is traditionally accepted even if it is still debated (Klewicki, 2010; Marusic et al., 2010). The outer region, which includes the overlap and defect layers, is usually considered to be the upper layer of the turbulent boundary layer (or pipe or channel flow) where viscous momentum transfer is negligible with respect to turbulent momentum transfer. In the viscous sublayer, the classical law of the wall for the wall-normal distribution of mean velocity is obtained by assuming that Reynolds stresses are negligible compared to viscous shear stresses

$$U^+ = \frac{U}{u_\tau} = y^+ \tag{2}$$

In the overlap layer, the matching of the inner and outer expressions for the total shear stress is usually performed in a manner that leads to the traditional log law

$$U^+ = \frac{1}{\kappa}\ln y^+ + B \tag{3}$$

where κ is the von Karman constant.

For large-defect TBLs, the mean momentum and turbulent energy balances are completely different and a widely accepted layer representation does not exist. By using asymptotic theory, Melnik (1989), Durbin and Belcher (1992), Bush and Krishnamurthy (1992) and Scheichl and Kluwick (2007) have each proposed different types of three-layer structures (inner/intermediate/outer). Other researchers, using asymptotic theory or dimensional and physical arguments, suggest various two-layer structures that represent either a gradual or an abrupt shift from the canonical structure as the velocity defect or pressure gradient increases (Afzal, 1983; 1996; Kader and Yaglom, 1978; Perry et al., 1966; 2002; Perry and Schofield, 1973; Skote and Henningson, 2002; Stratford, 1959; Townsend, 1961). In all these works, equilibrium or quasi-equilibrium is usually assumed, together with various other assumptions.

Some of these theories are tested in the present study. But since we cannot truly resolve the layer-structure issue, we use loosely