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Adverse Pressure Gradient Turbulent Boundary Layer Flows: Part 1: Flow Development

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Abstract

A progress report is presented of the authors' recent work on the scaling of adverse pressure gradient turbulent boundary layer flows. In the first part, flow classification is presented based on mean deficit scaling. A fully developed equilibrium condition is defined based on the Zagarola and Smits scaling. This definition agrees with the constant pressure parameter definition of Castillo and George.

Introduction

Adverse pressure gradient boundary layers have been of interest due to their common presence in engineering applications. The challenges associated with the development of proper scales with which to describe these flows, have attracted considerable attention [Clauser, Castillo and George]. Extensive work of the authors [1, 2, 5, 6, 8] has shown that the classical scaling of the mean deficit profiles with the friction velocity, u_*, does not hold for these flows. Neither does the Castillo and George scale of U_e where U_e is the free stream velocity. It has been shown by the authors that using the scale of Zagarola and Smits [17, 18], as suggested by Castillo and George [7], it is possible to observe the flow development to a fully developed stage. It has been further shown that this fully developed stage is the one referred as the equilibrium stage in data from the earlier APG work of Clauser [9], Bradshaw [3, 4] and Newman [15]. The objective of this two-part paper is to give a progress report of the authors' recent work, while providing additional insight. In the first part, flow development is described based on the characterization of mean deficit profiles. In the second part, Reynolds stresses are examined with a view to the development of a new scale.

Experimental Setup and Pressure Gradient

Two new flows, Flow A and B, have been generated using the Victoria University Research Wind Tunnel. The wind tunnel is a blower-type with a 1.3m diameter fan. The 4.5 m long test section is fitted with an adjustable, flexible top that is set to form a plane diffuser shape. By changing the top shape, it is possible to generate different adverse pressure gradient conditions on the boundary layer that is growing on the bottom floor. The pressure distribution is measured by a series of static pressure taps along the centerline of the floor. In Figure 1, the dimensionless pressure distribution is presented as the pressure coefficient, Cp, for four flows. Flow A and Flow Han [11] were designed to have a similar pressure distribution to that of Flow 141 of the 1980 Stanford Conference [12] contributed by Samuel and Joubert [16]. Flows A, B and Han were generated in the Victoria University Wind Tunnel. Flows 141, Han and A are *increasingly* APG flows, as seen in Figure 1. Flow B was designed to contrast with these flows by having only a short increasingly APG region followed by a longer *decreasingly* APG region. The experimental data form these four flows are compared in detail below with the data of Clauser [9], Bradshaw [3, 4] and Newman [15].

For Flows Han, A and B, a reference velocity of 22 m/s was held constant at the test section inlet. DANTEC 55P05 boundary layer type single wire probes and DANTEC 55R51 x-wire probes were used for hot-wire measurements with a DANTEC streamline CTA system and Streamware software. On the single wire probes, the sensing wires are defined with gold plating on a platinum plated tungsten core of 5 μm nominal core diameter. The x-wire probes have nickel film deposited on 70μm diameter quartz core. For single wire measurements, 524,288 samples were collected at each point at 100 kHz. For x-wire measurements, 262,144 samples were collected with a sampling frequency of 10 kHz. For single wire calibration, look-up tables are used. For x-wire calibration, the pitch/yaw method suggested in [19] as detailed in [14] is used.

Mean Velocity Deficit Scaling

In Figure 2, the classical APG data of Clauser [9], Bradshaw [3, 4] and Newman [15] are presented with the Zagarola and Smits scaling of $U_e\delta^*/\delta$. These flows all have decreasingly APG. They are referred as Flows 2200, 2300, 2500, 3300, and 3500, respectively, in the 1968 Stanford Conference [10].

In Figure 2, a collapse of the mean deficit profiles is evident. Statistical means are applied to the data from these flows to define a curve representing the average collapse. The standard error of this curve is used to define a band of the acceptable collapse. The average line and upper and lower limit are also shown in Figure 2. This band is used to classify developing APG boundary layer flows. Similarly, 12 velocity profiles from the favorable pressure gradient (FPG) flow of Ludweig and Tillman [13] is used to determine an average FPG behavior.

In Figure 3, $U_e\delta^*/\delta$ scaling has been applied to the mean velocity deficit of Flows 141, Han, A and B. The average APG and FPG lines are given to indicate the predicted behavior for these flows. All the flows demonstrate velocity profile behaviours that range from FPG to APG behavior. Even though based on the pressure distribution, Flows A, B and Han exhibit short regions of FPG, none of the velocity profiles presented come from an FPG region. Thus, it is evident all flows are demonstrating flow development from FPG type behavior to APG type behavior.

In Figure 4, the mean deficit profiles that fall within the acceptable range in Figure 3, are repeated. The acceptable range is as defined in Figure 2. These profiles are considered to be in the fully developed region, defining a state of equilibrium. In Flows 141, Han, A and B, this region corresponds to consecutive longitudinal locations towards the end of the test section. The upstream measurements do not fall within the APG band, indicating that the flow had not developed to an APG equilibrium state.

Pressure Parameter L_q

In Castillo and George [7], equilibrium is defined with the pressure parameter, Λ_θ, given in Equation (1). When Λ_θ is constant, the boundary layer flow is expected to reach an equilibrium state. Three different constants are expected for ZPG, FPG and APG boundary layers.

$$\Lambda_\theta = \frac{\theta}{U_e \, d\theta/dx} \frac{dU_e}{dx} \qquad (1)$$

In Figure 5 the pressure parameter is presented for Flows 141, Han, A and B. The shaded band highlights where the parameter becomes almost constant, and hence, where equilibrium is reached. The onset of equilibrium as defined in this manner, agrees with the definition of the acceptable band of $U_e\delta^*/\delta$ scaling. A star is used to indicate the position of the first mean deficit profile which lies within the acceptable APG equilibrium band. For all four flows, the location of the star coincides with the point where Λ_θ is seen to have become constant.

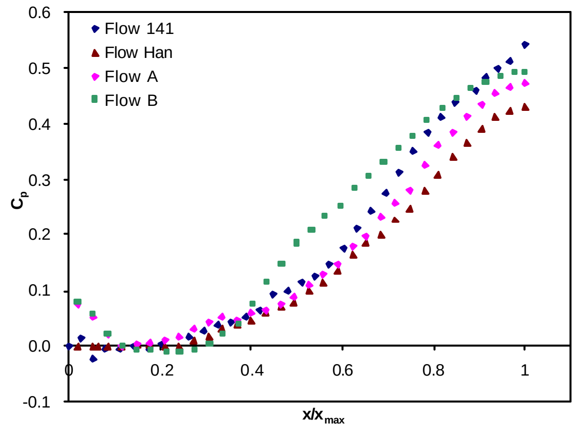


Figure 1. Pressure distribution for Flows 141, Han, A and B.

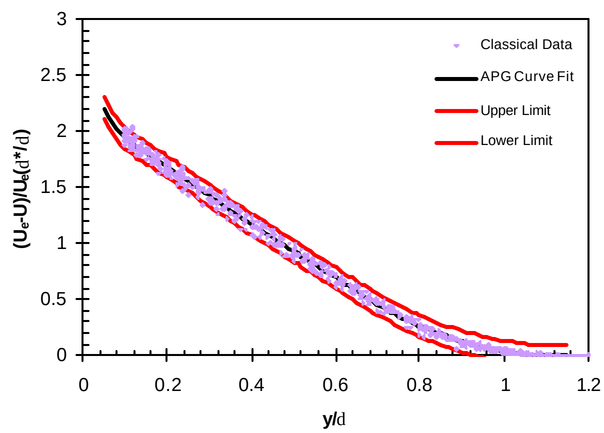
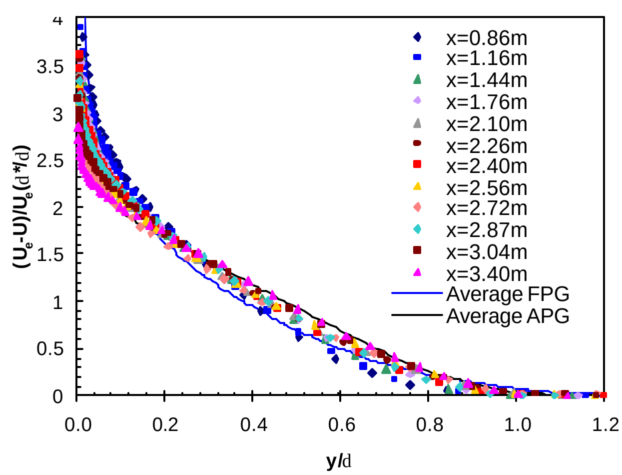


Figure 2. Mean velocity deficit profiles scaled with $U_e\delta^*/\delta$. Flows 2500, 3300, 2200, 2300 and 3500 [10] of Bradshaw [3, 4], Clauser [9] and Newman [15], respectively. The upper and lower limits shown with the line of average collapse, are used to define the acceptable collapse of APG flow data.



3a) Flow 141

Conclusions

An equilibrium state for adverse pressure gradient boundary layer flows can be defined by a constant pressure parameter, Λ_θ. When the flow is in this equilibrium state, the mean velocity deficit profiles, collapse to a single profile when scaled with $U_e\delta^*/\delta$.

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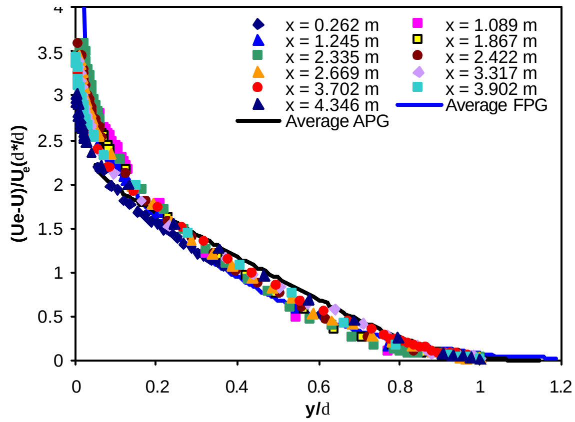
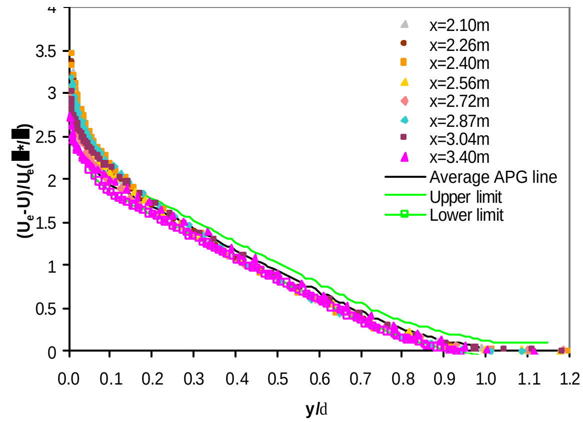
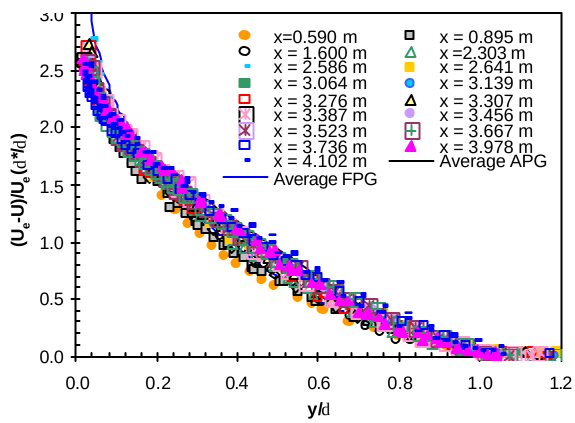


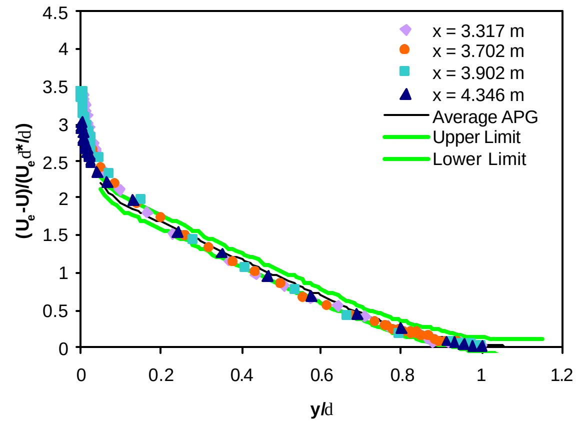
3b) Han



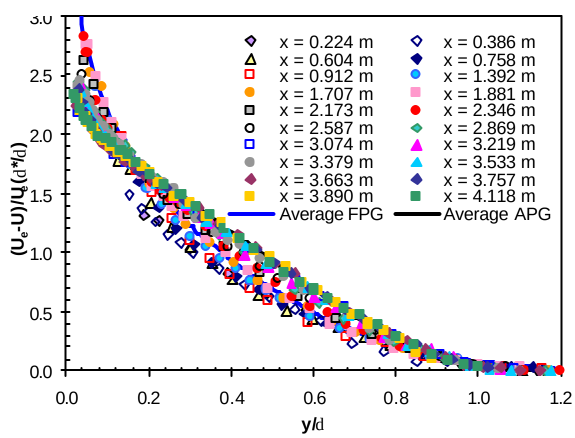
4a) Flow 141



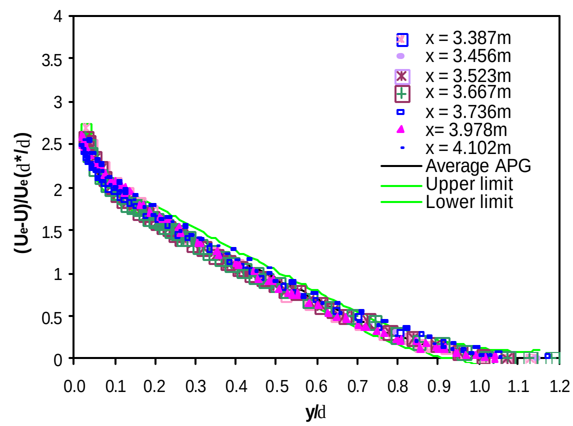
3c) Flow A



4b) Flow Han

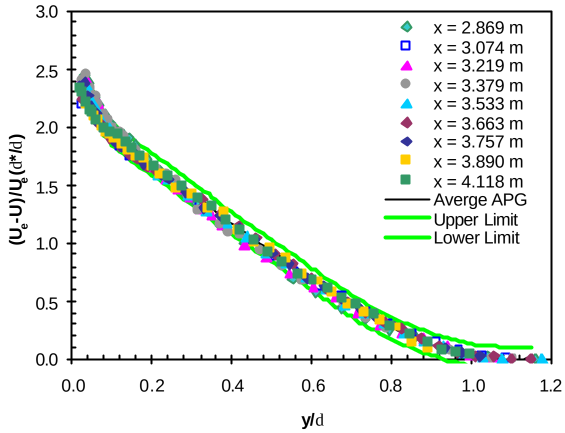


3d) Flow B



4c) Flow A

Figure 3. Mean velocity deficit profiles scaled with $U_e\delta^*/\delta$. The solid lines correspond to the average collapse of classical APG data of Clauser [9], Bradshaw [3, 4] and Newman [15], and average collapse of FPG data from Ludweig and Tillman [13].



4d) Flow B

Figure 4. Mean velocity deficit profiles scaled with $U_e\delta^*/\delta$ for Flow 141 4a), Flow Han 4b), Flow A 4c) and Flow B 4d). Only the velocity profiles which fall within the acceptable APG equilibrium band are given.

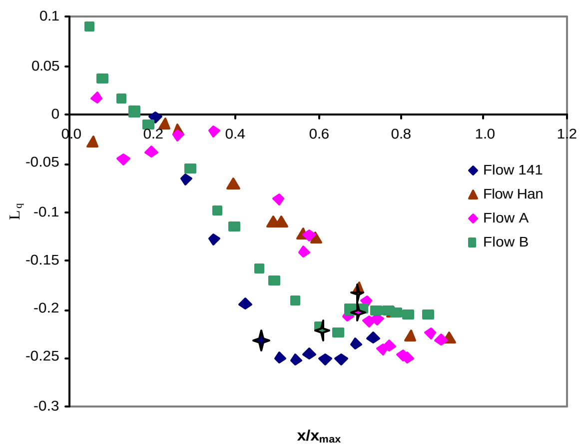


Figure 5. Pressure parameter Λ_θ for Flows 141, Han, A and B. The star represents the first longitudinal location which is within the acceptable APG equilibrium band with $U_e\delta^*/\delta$ scaling.

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