IMPACT OF PRESSURE-GRADIENT CONDITIONS ON HIGH REYNOLDS NUMBER TURBULENT BOUNDARY LAYERS

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Summary Mean velocity distributions in the overlap region, over the range of Reynolds numbers $10{,}000 < Re_q < 70{,}000$, under five different pressure-gradient conditions are accurately described by a log law. The pressure-gradient conditions include adverse, zero, favorable and strongly favorable. The wall-shear stress was measured using oil-film interferometry, and hot-wire sensors were used to measure velocity profiles. Parameters of the logarithmic overlap region developed from these higher Reynolds number boundary layers continue to be consistent with our recent findings and to remain independent of Reynolds number. The best estimate of the log-law parameters from the zero-pressure gradient boundary layers is $k = 0.38$, $B = 4.1$. However, the Kármán "coefficient" (k) is found to vary considerably for the non-equilibrium boundary layers under the various pressure gradients. The results highlight the variation with pressure gradient not only in the outer region of the boundary layer but also within the inner region.

INTRODUCTION & EXPERIMENTAL ARRANGEMENT

Two independent experimental investigations of the behavior of turbulent boundary layers with increasing Reynolds number (Re_q) were recently completed [1]. The experiments were performed in two facilities, the MTL wind tunnel at KTH and the NDF wind tunnel at IIT. While the KTH experiments were carried out on a flat plate, the model used in the NDF was a long cylinder with its axis aligned in the flow direction. Both experiments were conducted in a zero-pressure gradient, covered the range of Reynolds numbers based on the momentum thickness from 2,500 to 27,000, and utilized oil-film interferometry to obtain an independent measure of the wall-shear stress. Contrary to the conclusions of some earlier publications, careful analysis of the data revealed no significant Reynolds number dependence for the parameters describing the overlap region using the classical logarithmic relation. The parameters of the logarithmic overlap region were found to be constant and were estimated to be: $k = 0.38$, $B = 4.1$. These two experiments have been recently extended to Reynolds numbers based on momentum thickness exceeding 70,000. The current experiments were also carried out in the National Diagnostic Facility (NDF) at IIT on a 10 m long and 1.5 m wide flat plate using free-stream velocities ranging from 30 to 85 m/s. Again, hot-wire anemometry and oil-film interferometry were used to measure the velocity profiles and the wall-shear stress, respectively. The design of the experiments, and in particular the location and spacing of the velocity profiles in the downstream direction and the hot-wire sensor in the wall-normal direction, developed to facilitate the evaluation of wall-normal *and* streamwise derivatives. The arrangement of the NDF was designed to allow the adjustment of the test-section ceiling to impart various pressure gradients. Several conditions were investigated so far, including: Adverse Pressure Gradient (APG), Zero Pressure Gradient (ZPG), Favorable Pressure Gradient (FPG), Strongly Favorable Pressure Gradient (SFPG), and Complex Pressure Gradient (CPG) as displayed in Figure 1.

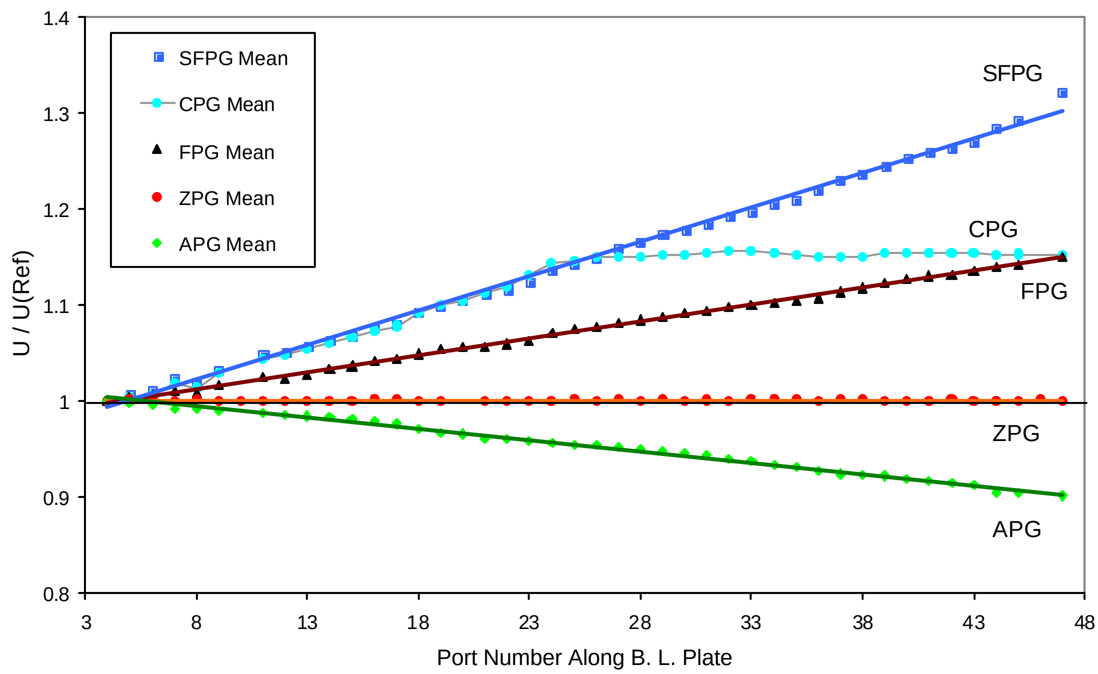

Figure 1. Variation of free-stream velocity along 10 m long boundary layer plate for various pressure-gradient conditions

RESULTS

One of the cornerstones of our approach to measurements of turbulent wall-bounded flows is the *independent* and accurate measurement of the wall shear stress with oil-film interferometry. We believe the only wall-bounded flow that may not require such measurements is the *fully developed* pipe flow, where the careful measurement of pressure gradient can lead to an accurate determination of the friction velocity. For the non-equilibrium boundary layers under various pressure-gradient conditions, one can be dramatically misled by other indirect techniques for the determination of wall-shear stress. Figure 2 compares our recent ZPG measurements with the recent two sets of measurements of Hites and Österlund. The value of the Kármán constant extracted using the correlation proposed by Fernholz [2] and all three sets of data is approximately 0.38.

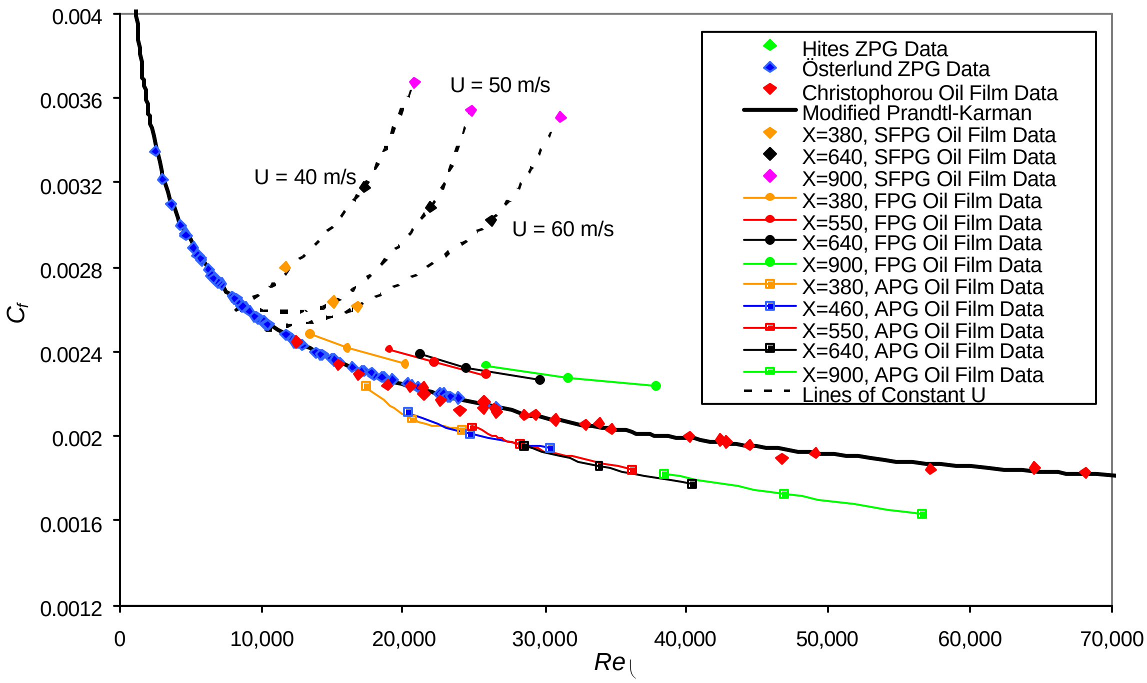

Figure 2. Variation of skin friction with momentum-thickness Reynolds number for different streamwise positions and free stream velocities.

A few samples of pressure-gradient data are included in Figure 2. In particular, the behaviour of the non-equilibrium layers with the SFPG is most revealing when contrasted to the equilibrium ZPG data where the resulting skin friction is independent of whether Re_q is varried by changing the free-stream velocity or the downstream distance. As in our earlier work [1], profiles of the mean and rms streamwise component of the velocity and their spatial derivatives are used to examine the effects of the pressure gradient on the inner and outer layers as well as their overlap region. The results demonstrate that the pressure gradient causes significant changes not only in the outer region of the boundary layer but also within the inner region; i.e., the buffer layer. The effect of these changes on Coles' outer layer parameter and the behavior of the maximum turbulence stress have also been documented.

CONCLUSIONS

A number of yet unexplained differences between wall-bounded turbulent flows in pipes [3], channels [4] and boundary layers are discussed and clarified based on the comparison between our recent measurements in ZPG boundary layers and the present results for different pressure gradients. The variation of the Kármán "coefficient" (k) from generally accepted values is revealed by these measurements in both equilibrium and non-equilibrium wall-bounded shear flows.

References

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