Pressure-gradient effects on turbulent boundary layers with square ribs

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Abstract Turbulent flows with the inclusion of ribs are encountered in several engineering applications. For example, arrays of ribs or rib turbulators are strategically employed in the cooling system of gas turbines, nuclear reactors and in heat exchangers to enhance convective heat transfer. Due to its practical relevance, simplified scenarios, such as the inclusion of ribs in zero-pressure-gradient (ZPG) turbulent boundary layer (TBL) developing over a flat plate, have been investigated over the years in order to understand the effects of roughness inclusion on drag characteristics and turbulence structure. Unfortunately, most flows of relevance in technical applications are exposed to pressure gradients in which the applicability of the knowledge from ZPG TBL flows is restricted. The interaction of the pressure-gradient effect with the roughness elements changes the flow structure and, as consequence, the drag performance is altered. Moreover, previous studies has shown that adverse-pressure-gradient (APG) flows are characterized by a reduced friction without a drop in the convective heat transfer coefficient [1], paving the way for the design of high-performance heat exchangers. Despite this, the studies in the literature mainly focus on backward-facing steps or channel flows [2, 3]. These studies highlight that the reattachment length is increased with the intensity of the adverse pressure gradient. It was also concluded that the reattachment length under the effect of a non-constant increasing streamwise adverse pressure gradient was larger than its constant counterpart. In channel flows with turbulent square ribs [4], it was shown that the APG affects the flow statistics across a larger portion of the channel when compared with the flow under favourable pressure gradient (FPG). Unfortunately, most of these studies suffer a lack of characterization of the inflow conditions and, above all, of the pressure-gradient parameters, which substantially hinders the generalization of the results. It is well known that the investigation of APG TBLs involves a larger parametric space than ZPG, which includes not only the local pressure gradient but also its upstream (pressure-gradient) history in the evolution of the TBL [5, 6]. One of the most popular parameters used to characterize the pressure-gradient strength is $\beta = \delta^*/\tau_w \mathrm{d}P/\mathrm{d}x$, where δ^* is the displacement thickness, τ_w is the mean wall-shear stress, and $\mathrm{d}P/\mathrm{d}x$ the pressure gradient along the streamwise direction. Note that β quantifies the relative importance of the forces due to the local pressure gradient and shear stress [7]. Due to its practical relevance in the study of APG TBLs, it is of the deepest relevance to determine if β is a useful parameter for the analysis of APG TBL flows with ribs. Assuming this is the case, it is quite interesting to assess how the pressure gradient affects the wake downstream of the rib and the flow structures present in the flow. This knowledge would allow determining whether streamwise pressure gradients could be used to control the flow-field features in TBLs with wall-attached ribs. The present contribution aims therefore to study the structure of turbulent flows with and without wall-attached square ribs that are under the effect of different pressure gradients (favourable and adverse), and without a pressure gradient. To this end, an experimental campaign was carried out at the Göttingen type wind tunnel of the Aerospace Engineering Group at the Universidad Carlos III de Madrid. Particle Image Velocimetry (PIV) measurements were performed at a Reynolds number based on friction velocity equal to 950 and a rib height equal to 0.3 times the boundary-layer thickness. The desired pressure-gradient conditions were established by means of wall inserts that allow obtaining a Clauser pressure-gradient-parameter of β =-0.14, 0 and 1.3. An enhanced-resolution EPTV approach (Ensemble Particle Tracking Velocimetry) procedure is applied to obtain the different turbulent statistics and the SPIV software is used to calculate the velocity fields. Utilizing modal analysis based on Proper Orthogonal Decomposition, the flow-field features are discussed, and the combined effects of roughness and pressure gradient assessed. The mean velocity fields for the three cases are shown in Fig. 1 with superposed streamlines. It is interesting to note that the recirculation bubble increases in size when increasing β. This behaviour differs from the one found in turbulent channels, where the recirculation region center was observed to be almost independent of the pressure gradient [8]. The reattachment length of the ZPG case is larger than past cubes, reaching more similar values to those observed by Ra and Chang [3] for backward-facing steps. This effect can be explained by the increase of wall-normal convection due to the APG. It is worth noting here that, as expected due to the small β value obtained, the case under FPG exhibits only minor differences with respect to the ZPG case. This result supports the observation that β is very relevant when analyzing the pressure-gradient effect on the local flow organization.

Keywords: Turbulent boundary layer, Pressure gradient flows, Ribs

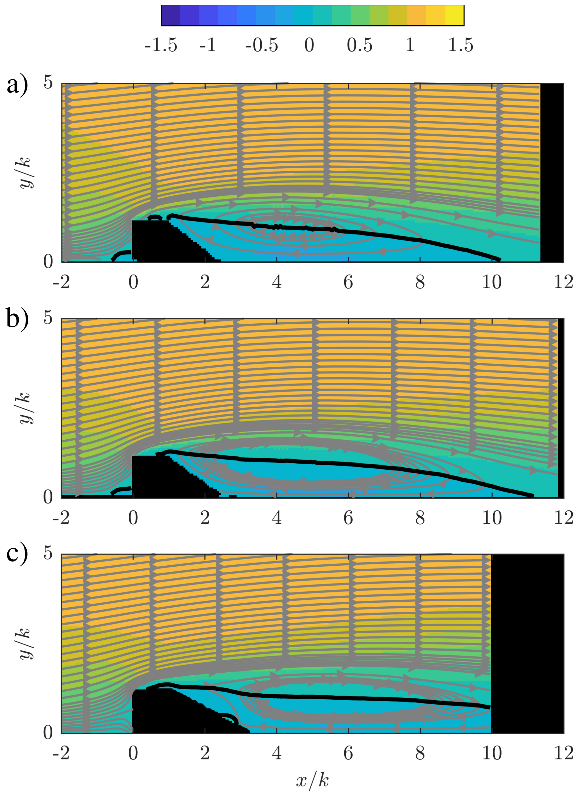

Fig. 1 Mean streamwise velocity fields U/U_∞ as a function of the streamwise and wall-normal coordinates (x and y) normalized with the obstacle height k. From top to bottom: a) FPG, b) ZPG, and c) APG. Grey lines represent the flow streamlines and the solid black line represents the contour of zero velocity. Areas in the final part of the image in which the laser illumination was not sufficient are blanked in black color.

References

[1] Houra, T, Nagano, Y (2006) Effects of adverse pressure gradient on heat transfer mechanism in thermal boundary layer. *International Journal of Heat and Fluid Flow*, vol. 27, pp 967-976. doi: 10.1016/j.ijheatfluidflow.2006.03.019

[2] Kuehn, D A D (1980) Effects of adverse pressure gradient on the incompressible reattaching flow over a rearward-facing step. *AIAA Journal*, vol. 18, pp 343-344. doi: 10.2514/3.50765

[3] Ra, S H, Chang, P K (1990) Effects of pressure gradient on reattaching flow downstream of a rearward-facing step. *Journal of Aircraft*, vol. 27, pp 93-95. doi: 10.2514/3.45901

[4] Shah, M K and Tachie, M F (2008) Flow relaxation past a transverse square rib in pressure gradients. *AIAA Journal*, vol. 46, pp 1849-1863. doi: 10.2514/1.35528

[5] Bobke, A, Vinuesa, R, Örlü, R , Schlatter, P (2017) History effects and near equilibrium in adverse-pressure-gradient turbulent boundary layers. *Journal of Fluid Mechanics*, vol. 820, pp 667-692. doi: 10.1017/jfm.2017.236

[6] Sanmiguel Vila, C, Örlü, R, Vinuesa, R, Schlatter, P, Ianiro, A, Discetti, S (2017) Adverse-pressure-gradient effects on turbulent boundary layers: statistics and flow-field organization. *Flow, Turbulence and Combustion*, vol. 99, pp 589-612. doi: 10.1007/s10494-017-9869-z

[7] Clauser, F H (1954) Turbulent boundary layers in adverse pressure gradients. *Journal of the Aeronautical Sciences*, vol. 21, pp 91-108. doi: 10.2514/8.2938

[8] Shah, M K and Tachie, M F (2009) PIV investigation of flow over a transverse square rib in pressure gradients. *Journal of Turbulence*, vol. 10, N39. doi:10.1080/14685240903193311