THE EFFECTS OF EXTERNAL CONDITIONS IN TURBULENT BOUNDARY LAYERS

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ABSTRACT

The effects of multiple external conditions on turbulent boundary layers were studied in detail. These external conditions include: surface roughness, upstream turbulence intensity, and pressure gradient. Furthermore, the combined effects of these conditions show the complicated nature of many realistic flow conditions. It was found that the effects of surface roughness are difficult to generalize, given the importance of so many parameters. These parameters include: roughness geometry, roughness regime, roughness height to boundary layer thickness, (k/δ), roughness parameter, (k^+), Reynolds number, and roughness function (ΔB^+). A further complication, is the difficulty in computing the wall shear stress, τ_w/ρ. For the sand grain type roughness, the mean velocity and Reynolds stresses were studied in inner and outer variables, as well as, boundary layer parameters, anisotropy tensor, production term, and viscous stress and form drag contributions.

To explore the effects of roughness and Reynolds number dependence in the boundary layer, a new experiment was carefully designed to properly capture the x-dependence of the single-point statistics, where consecutive measurements of eleven streamwise locations were performed. Consequently, the skin friction was obtained within 3% and 5% accuracy for smooth and rough surfaces, respectively, using the full boundary layer equations. With accurate calculations of the skin friction coefficient, the viscous stress and form drag contributions can be realized for ZPG flows. It was found that roughness destroys the viscous layer near the wall, thus, reducing the contribution of the viscous stress in the wall region. As a result, the contribution in the skin friction due to form drag increases, while the viscous stress decreases. This yields Reynolds number invariance in the skin friction, near-wall roughness parameters, and inner velocity profiles as k^+ increases into the fully rough regime. However, in the transitionally rough regime, (i.e., $5 < k^+ < 70$), it was found that these parameters are functions of both Reynolds number and roughness.

For the sand grain type roughnesses, only the Zagarola and Smits scaling, $U_\infty \delta^*/\delta$, is able to remove the effects of roughness and Reynolds number from the

velocity profiles in outer variables, provided there is no freestream turbulence. However, each scaling for the velocity deficit profiles results in self-similar solutions for fixed experimental conditions. When examining the Reynolds stresses in the inner region, (i.e., $0 < (y + \epsilon)^+ < 0.1\delta^+$), the $< u^2 >$ component shows the largest influence of roughness, where the high peak near the wall was decreased and became nearly flat for the fully rough regime profiles. In addition, the Reynolds stresses in outer variables show self-similarity for fixed experimental conditions. However, as the roughness parameter, k^+, increases, all Reynolds stress profiles become similar in shape indicating increased isotropy near the wall. Furthermore, the boundary layer parameters and production terms also show a considerable increase due to roughness.

This study of rough wall turbulence was also combined with high freestream turbulence. The freestream turbulence was generated with the use of an active grid, which resulted in freestream turbulence levels of 6.2% and 5.2% at the two downstream measuring locations. The effect of the freestream turbulence on this rough surface significantly alters the mean velocity deficit profiles. In inner variables, the velocity profiles show a significantly reduced wake region, while in outer variables, a more full profile indicates increased momentum transport towards the wall. Furthermore, the effects of freestream turbulence are clearly identifiable in the Reynolds stress profiles. The streamwise Reynolds stress, $< u^2 >$, is the most affected by the high freestream turbulence, where deviations exist throughout the entire boundary layer. In addition, a noticeable difference between the smooth and rough surface triple correlations exist near the wall, but no significant differences are seen due to freestream turbulence. In the outer region, however, a more noticeable difference exists due to the turbulent diffusion from the freestream turbulence. An investigation of the complete Reynolds stress equations indicates that the turbulent diffusion becomes an important term in the streamwise Reynolds stress equation, given that the production of $< u^2 >$ is actually reduced when high turbulence intensity is present. The additional effect of freestream turbulence also increases the skin friction up to 20%, which can actually delay separation, if subjected to an adverse pressure gradient.

Furthermore, pressure gradient flows are also difficult to generalize, given that a significant difference in the boundary layer structure exists between different external pressure gradients, (i.e., FPG, ZPG, and APG). This was examined through the scaling of the velocity and Reynolds stresses from multiple data sets. One of these scaling methods was derived from a generalized form of the similarity analysis of the Navier-stokes equations, originally proposed by George and Castillo (1997). It is clear that multi-point and multi-velocity scalings are needed to collapse velocity, Reynolds stresses, and higher order moments with different pressure gradients. Furthermore, the combined effects of surface roughness and pressure gradient also show how complex realistic flows are, and that multiple velocity scales are required.