TURBULENT BOUNDARY LAYERS: FREE-STREAM TURBULENCE, SURFACE ROUGHNESS AND FAVORABLE PRESSURE GRADIENT

By

Sheilla N. Torres-Nieves

A Thesis Submitted to the Graduate

Faculty of Rensselaer Polytechnic Institute

in Partial Fulfillment of the

Requirements for the Degree of

MASTER OF SCIENCE

Approved:

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Luciano Castillo
Thesis Adviser

Rensselaer Polytechnic Institute
Troy, New York

July 2007
(For Graduation August 2007)

ABSTRACT

The study of external conditions over turbulent boundary layers is of great importance for the understanding of common engineering problems. Earlier investigations on surface roughness and external pressure gradient have shown their effect on the mean velocity and Reynolds stress profiles. However, the role of the free-stream turbulence as an external condition is not completely understood, even for the simplest of flows (*i.e.*, the smooth, zero pressure gradient turbulent boundary layer). Consequently, the joint effect of these conditions are still uncertain and not well understood. Hence, the aim of this investigation is to study the effect of free-stream turbulence, external pressure gradient and surface roughness on the turbulent boundary layer.

New experiments are performed in the Corrsin wind tunnel facility at The Johns Hopkins University in order to identify the influence of free-stream turbulence and surface roughness over a favorable pressure gradient turbulent boundary layer. A 2D turbulent boundary layer experiment with a favorable pressure gradient (FPG) has been carried out over a rough surface using Laser Doppler anemometry (LDA). A 3.6 m-long flat plate, covered with a continuous abrasive sheet, was tilted 5^o in order to generate the external favorable pressure gradient. Furthermore, measurements with and without an active grid are performed at a wind tunnel speed of 10 m/s. Moreover, two different configurations of randomly rotating agitator winglets are employed as part of the active grid system. These resulted in free-stream turbulence levels ranging from 3.64% to 6.82%. Moreover, the experimental data is characterized by turbulent boundary layers with Reynolds number, based on momentum thickness, θ, between 2930 and 4230. For a given turbulence intensity (or Tu), two components of the velocity field, U and V, are measured at two distinct locations (*i.e.*, x=1.7 m and x=2.7 m). Measurements of the fluctuating components of the velocity and Reynolds shear stress profiles are also obtained. The measurement errors for the mean velocity and Reynolds stresses are less than 1% and 2%, correspondingly

In order to study the effects of free-stream turbulence, external pressure gradient and surface roughness, mean velocity deficit profiles, Reynolds stress profiles, boundary layer parameters, and skin friction are analyzed. The mean deficit profiles show the effects of these three external conditions. It is observed that free-stream turbulence alters the shape of the profiles for all the outer scaling techniques examined: classical scaling, George & Castillo scaling, and Zagarola & Smits scaling. Furthermore, Reynolds stress profiles are also affected by these conditions. For instance, free-stream turbulence increases the magnitude of the Reynolds stresses, making the values near the edge of the boundary layer to be non-zero. Moreover, it is confirmed that surface roughness changes the shape of the profiles. For instance, when normalizing with the classical scaling, it is seen that roughness prevents the streamwise Reynolds normal stress from increasing near the wall, mainly because of the destruction of the viscous regions close to the wall due to surface roughness. The effect of the external favorable pressure gradient also shows in the mean velocity profiles and turbulence fluctuations. The results obtained from this investigation certainly emphasize the need to develop new theories that can account for the multiple scales that are present in practical engineering flows.

In addition, the boundary layer parameters and the skin friction are influenced by these conditions. While the external pressure gradient and higher levels of free-stream turbulence result in a reduction to the shape factor, H, and the ratio between displacement thickness and boundary layer thickness, $\frac{\delta^*}{\delta_{95}}$, surface roughness increased their magnitude. Moreover, as expected from previous studies, this investigation confirmed that these three external conditions act to increase the skin friction. The skin friction values were calculated based on the constant shear layer equation.