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Experimental investigation of the effects of short roughness strip and wall suction on the anisotropy in a turbulent boundary layer

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ABSTRACT

Hot wire measurements have been made in a turbulent boundary layer subjected to a short roughness strip and concentrated suction. The suction is applied through a porous wall strip for a range of suction rate. The aim of the study is to examine the effects of short roughness strip and suction on the anisotropy of Reynolds stress tensor. The result indicates that the anisotropy of Reynolds stress tensor is increased marginally downstream of the combination of suction and roughness strip. Although, roughness strip control the magnitude of the variations of the effect of suction on the anisotropy of Reynolds stress tensor, they act independently on the mechanism of the wall turbulence of the layer. While suction acts to increase the anisotropy, roughness strip act to reduce the anisotropy.

1. Introduction

The ability to interfere with the structure of turbulent flows occurring in various engineering applications is of significant importance and benefit. The study of how turbulent shear flows respond to different perturbations presents interests from both fundamental and engineering points of views. The latter study can lead to an improvement in the effectiveness of flow control techniques [1,2]. From fundamental point of view, such study can improve our basic knowledge of the dynamical response of turbulent shear flows. For example, the manner in which near-wall coherent structures respond to a sudden change in boundary conditions such as the combination of a short roughness strip and suction could provide some insight into the interaction between the wall region and the outer part of the boundary layer. Pearson et al. [3] investigated the response of a turbulent boundary layer to a short roughness strip, using the Laser Doppler Velocimetry (LDV). They found that, relative to the undisturbed smooth wall, the roughness strip increased the turbulent stresses in the region between the two internal layers originating at the upstream and downstream edges of the strip. Smalley et al. [4] showed that, relative to a smooth wall, the drag augmenting roughness reduces the level of an anisotropy. Similarly, Leonardi et al. [5] found that Reynolds stresses and their anisotropy invariants showed a closer approach to an isotropy over the rough wall than over a smooth wall. Oyewola et al. [6] examined the combined influence of Reynolds number and localised wall suction on a turbulent boundary layer. Their results indicated that it is the combination of momentum thickness Reynolds number and the suction rate that controls the boundary layer response to suction. They also found that suction altered the redistribution of the turbulent kinetic energy between its components. Antonia et al. [7] and Fulachier et al. [8] applied suction uniformly over the wall and found that the large-scale motion is altered significantly by suction. Their anisotropy invariant map (AIM) indicated that, relative to the no suction case, suction increases the anisotropy of the layer, with the wall layer mostly affected. Also, Oyewola et al. [9] examined the effect concentrated wall suction can have on the anisotropy of Reynolds stress tensor. Their results indicated that the large-scale motion of the boundary layer was significantly altered by suction, and that the global anisotropy of the layer increases with the suction rate. For example, they found that the shape of the structures near the wall changed from a cigar to a pancake shape when suction is applied. Recently, Oyewola and Tomori [10] studied the combined effect of the short roughness strip and localised wall suction, on the evolution of anisotropy, in a turbulent boundary layer. Although, anisotropy was altered by the combination of suction and roughness, the latter study was not sufficiently wide in scope to assess the full influence of short roughness strip on the suction effect on the anisotropy of Reynolds stress tensor.

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The present study extends the work of Oyewola and Tomori [10] and experimentally investigates the effects of a short roughness strip and wall suction effect on the anisotropy in a turbulent boundary layer. The results are compared with those obtained when suction is applied only with the same value of σ ($\sigma = V_w b/\theta_o U_1$, where V_w is the suction velocity, b is the width of the porous strip, θ_o is the momentum thickness at the leading edge of the suction strip when no suction is applied and U_1 is the free stream velocity). The understanding of the presence study will aid the improvement of turbulence modelling especially in identifying the parameters to interfere with in order to achieve a significant level of control.

2. Experimental details and conditions

Experiments were made in a smooth flat plate turbulent boundary layer, which is subjected to the combination of short roughness strip and concentrated suction, applied through a short porous strip. The turbulent boundary layer develops on the floor of the wind tunnel working section (Fig. 1) after it is tripped at the exit from a two-dimensional 9.5:1 contraction using a 100 mm roughness strip (Norton Bear No. 40, very coarse). Tests showed that the boundary layer was fully developed at the suction strip location, which is about 1200 mm downstream of the roughness strip. The roof of the working section is adjusted to achieve the desired pressure gradient (zero for the present investigation). The free stream velocity, U_1, was approximately 7 ms^{-1}. A 3.25 mm thick porous strip with a width of 40 mm and made of sintered bronze with pore sizes in the range 40–80 μm or (0.4–0.9)ν/U_τ was mounted flush with the test section floor. Allowing for the width of the mounting recess step, the effective width (=b) of the strip was 35 mm. Suction was applied through a plenum chamber located underneath the suction strip and connected to a suction blower, driven by a controllable DC motor, through a circular pipe (internal diameter D=130 mm and $L/D \approx 38$, where L is the pipe length).

The flow rate Q_r was estimated directly by radially traversing a pitot tube located near the end of the pipe, for various values of the pipe centre-line velocity (U_c). A plot of Q_r vs. U_c allowed the suction velocity (V_w) to be inferred via the continuity equation ($Q_r = A_w V_w$, where A_w is the cross-sectional area of the porous strip). The suction velocity was assumed to be uniform over the porous surface; this assumption seems reasonable if the variation in the permeability coefficient of the porous material is $\pm 3\%$ [11,12].

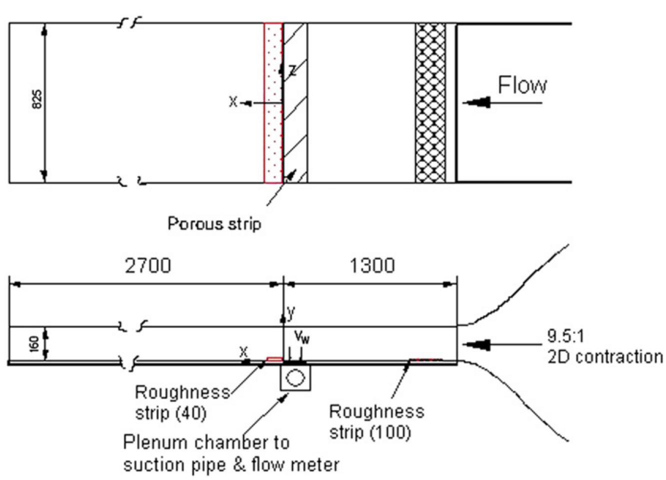

Fig. 1. Schematic arrangement of the experimental setup.

The short roughness strip made up of uniform sandpaper (40 grade) of 40 mm long in the streamwise direction and 1 mm above the smooth wall is placed just immediately after the suction strip. The initial momentum thickness Reynolds number $R_{\theta o}$ ($R_{\theta o} = U_1\theta_o/\nu$, where θ_o is the momentum thickness at the leading edge of the suction strip when no suction is applied) is 1400. The suction rate σ ($\sigma = V_w b/\theta_o U_1$, where V_w and b are the suction velocity and width of the porous strip, respectively) is in the range σ=0–5.5. Measurements of the velocity fluctuations in the streamwise and wall normal directions were made with hot cross wires, each inclined at nominally 45° to the flow direction. The etched portion of each wire (Wollaston, Pt-10% Rh) had a diameter of 2.5 μm, and a length to diameter ratio of about 200. The separation between the inclined wires was about 0.6 mm. The velocity fluctuation in the spanwise direction was also measured by rotating the same X-probe through 90°. All hot wires were operated with in-house constant temperature anemometers at an overheat ratio of 1.5. The uncertainties in the streamwise, wall normal and spanwise velocity components are 3%, 5% and 4%, respectively.

3. Measurement results and their discussion

The distribution of the turbulent kinetic energy (K.E.=1/2 ($\langle u^2\rangle + \langle v^2\rangle + \langle w^2\rangle$) at x/δ_o=3.5 (δ_o is the boundary layer thickness at the leading edge of the suction strip when no suction is applied)) is shown in Fig. 2 for both suction and combination of suction and roughness. Also shown in the figure is the data for σ=0 (no suction) to provide a reference against which the effect of suction and roughness could be assessed. Important variation occurs in the distribution, relative to the undisturbed case. For example, in all cases, the data show a considerable reduction relative to the no suction case. The reduction being stronger for σ=5.5 near the wall. The reduction suggests a possible alteration in the redistribution of the turbulent kinetic energy among Reynolds stresses. This may reflect a possible structural change in the boundary layer, due to the modification of the near-wall structure. However, the influence of roughness strip on the suction is apparent throughout the boundary layer. The roughness strip modulates the magnitude and wavelength of the distribution, as shown in Fig. 2. For example, the reduction observed when σ=5.5 is reduced at the presence of the roughness strip. This is also true for other combination of suction and roughness strip. This scenario may suggest that turbulence is enhanced downstream of the strip, due to the interaction between the wall and the roughness elements. However, it seems that the pattern of the distribution is not being affected by the presence of the roughness

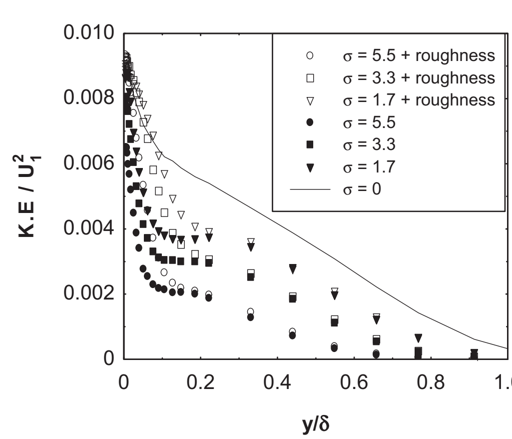

Fig. 2. Distribution of the turbulent kinetic energy. Closed symbols: suction, open symbols: combination of suction and roughness strip.