BRIEF COMMUNICATIONS

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The effect of three-dimensionality on a laminarizing boundary layer

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Measurements of highly accelerated turbulent boundary layers with and without mean cross-flow are presented and compared. The accelerated mean longitudinal velocity profiles suggest that the Reynolds shear stress, $\overline{u'v'}$, is greater in the two-dimensional case than in the three-dimensional case. The measured normal longitudinal Reynolds stress, $\overline{u'u'}$, is greater in the three-dimensional accelerated boundary layer case. The measurements indicate that the Reynolds stress tensor components decouple in the three-dimensional case; hence, the three-dimensionality alters the characteristic of nondecoupling observed in highly accelerated two-dimensional boundary layers. © *1995 American Institute of Physics.*

The study reported in this Brief Communication is motivated by highly accelerated three-dimensional (3-D) flows observed, for instance, in turbomachinary and curved nozzles. While the independent effects of boundary layer acceleration and three-dimensionality have been previously reported in the literature, little is known about the combined effect. It is well known that a turbulent boundary layer that has developed on a flat plate under a constant pressure gradient can experience relaminarization when subjected to a strong favorable pressure gradient (see, for example, the review by Narasimha and Sreenivasan[1]). The phenomenon is characterized by the decrease in the skin friction coefficient, a deviation from the law of the wall, and a decrease in velocity fluctuations relative to the free-stream velocity. Typically, relaminarization is characterized by the acceleration parameter, $K=\nu U'/U^2$, where U is the local free-stream velocity, U' is the derivative in the streamwise direction, and ν is the kinematic viscosity. This is an outer-layer parameter, since it carries no information about the boundary layer and hence cannot independently characterize the relaminarization phenomenon. Nonetheless, it is generally believed that sustained acceleration levels of $K>2.8\times10^{-6}$ will relaminarize the flow.[2]

A 3-D turbulent boundary layer (3-DTBL) is a wall-attached shear layer in which both velocity components parallel to the wall vary with distance from the wall. Several recent studies have revealed some common characteristics for 3-DTBLs without high streamwise acceleration (see the review by Johnston and Flack[3]). First, the wall-parallel shear stress vector lags the strain rate vector, thus preventing isotropic eddy viscosity models from properly predicting the flow. Second, the ratio of the turbulent shear stress to the turbulent kinetic energy is significantly lower in 3-DTBLs than in 2-DTBLs, which indicates that each Reynolds stress tensor component is responding differently to the addition of the cross-flow. The term "decoupled" is used here to indicate that the relative magnitudes of the Reynolds stress tensor components change. In 3-DTBLs the decoupling is a function of both the local cross-stream pressure gradient and the history of the boundary layer (i.e., $u'v'/q^2$ is a function of dP/dz and Reynolds number, where q^2 is the turbulent kinetic energy). This is not a disequilibrium effect, since typical 2-DTBL stress levels are not obtained if the three-dimensionality persists for a long distance. In contrast, the Reynolds stress tensor components are not decoupled in the highly accelerated two-dimensional (2-D) flows described above (Narasimha and Sreenivasan[1] show that $\overline{u'v'}/\sqrt{\overline{u'u'}}\sqrt{\overline{v'v'}}$ is constant with varying K).

One recent study of the combined effect of acceleration and three-dimensionality was performed by Launder and Loizou,[4] who examined the flow through a converging curved duct of a rectangular cross section. The authors concluded that the resulting flow was a combination of the effects observed from independent acceleration and curvature, however, they did not explicitly isolate the effects. The objective of this Brief Communication is to present data collected in a 3-D boundary, which is simultaneously accelerated. The results are compared to a similarly accelerated boundary layer with zero mean cross-flow.

The experiments were performed in a 7.6×30.5 cm low-speed wind tunnel with a nominal inlet velocity of 8.0 m/s and a free-stream turbulence intensity of 0.2%. All measurements were performed in the tunnel–floor boundary layer that was tripped 5 cm downstream of the test section inlet. The boundary layer developed over a distance of 90 cm before encountering a free-stream acceleration produced by a wedge-shaped obstacle attached to the ceiling of the tunnel, as illustrated in Fig. 1. Two different wedges were used; one

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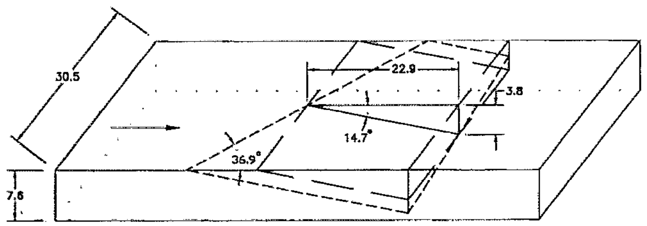

FIG. 1. The tunnel configuration. The tunnel walls are shown by the solid and dotted lines. The long dashed lines denote the 2-D wedge and the short dashed lines denote the 3-D wedge. The wedges coincide on the tunnel centerline, as shown with solid lines. Dimensions are in centimeters.

with the leading edge normal to the free stream and the other wedge swept at 36.9°. The latter wedge produced moderate turning of the flow. The wedges have the identical shape (and hence the same free-stream acceleration) along the tunnel centerline. In both cases, the acceleration parameter, K, was approximately equal to 3.5×10^{-6} at each measurement location under the wedge.

The velocity was measured with a TSI boundary layer probe (model 1218-T1.5) strung with a 5 μm diam platinum-coated tungsten wire. The probe was connected to a TSI constant temperature anemometer (model 1050) operating at a resistance ratio of 1.8. The initial position of the probe was set by observing the circuit resistance between the probe prongs and a 0.005 cm thick gauge that was lying flat on the tunnel floor. This technique showed excellent repeatability. A cross-wire was not used for measuring this flow due to the large size of the probe relative to the accelerated boundary layer thickness. The flow turning angle in the three-dimensional case was measured by carefully nulling a three-hole pressure probe. The probe was constructed of three 0.04 cm inner diameter tubes, soldered together in a plane with 0.07 cm center-to-center spacing. The mean velocity has an uncertainty of ±3% of the local streamwise velocity. The fluctuating velocity has an uncertainty of ±5% of the local value. All measurements are repeatable to within the stated uncertainty.

All measurements were performed on the centerline of the tunnel at 15.2, 7.6, and 0 cm upstream and 7.6, 15.2, and 22.9 cm downstream of the leading edge of the wedge. The data presented here are for the locations 15.2 cm upstream and downstream of the leading edge. The upstream location is sufficiently far upstream to be unaffected by the favorable pressure gradient induced by the wedge. The downstream location is representative of the flow at all of the measurement locations in the favorable pressure gradient region. For the 3-D wedge, the turning angle (with respect to the tunnel sidewalls) at this location is 7.0° in the free stream and gradually increases to a peak value of 11.0° at $y=0.25$ cm. This turning angle is smaller than that generally observed in previous 3-DTBL studies (see, for example, Anderson and Eaton[5] and Schwarz and Bradshaw,[6] who observed peak turning angles greater than 50° relative to the tunnel sidewalls). The turning angle observed here is comparable to that observed by Littell and Eaton[7] in the turbulent boundary layer on a rotating disk (peak turning angle of 12.0°). The turning angle in this flow is sufficient to observe fundamental differences between the 2-D and 3-D accelerated flows.

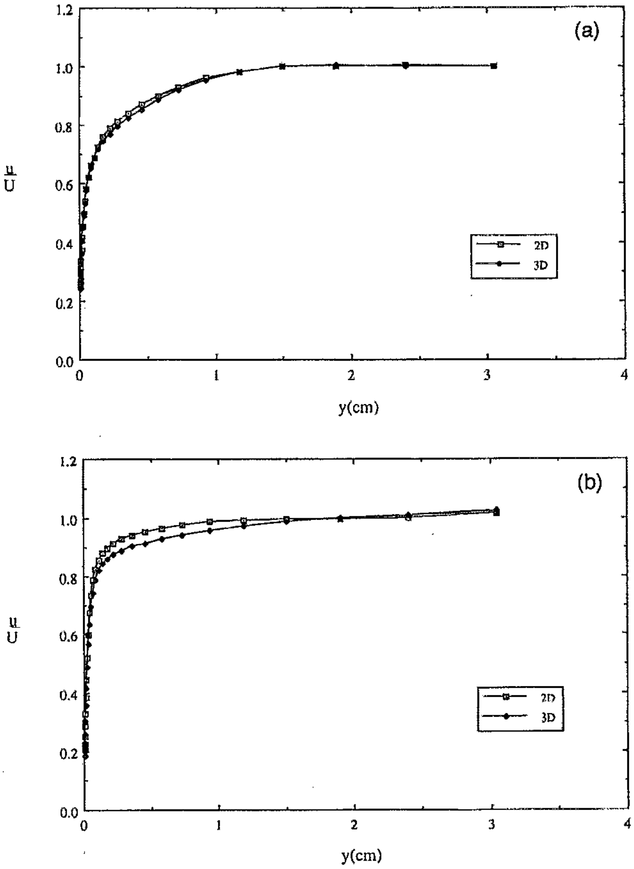

FIG. 2. The mean velocity profiles at 15.2 cm (a) upstream and (b) downstream of the leading edge of the wedge.

The mean longitudinal velocity profiles are shown in Fig. 2. For both cases in Fig. 2(a), the Reynolds number based on momentum thickness ($\mathrm{Re}_\theta=\theta U/\nu$) is approximately 650. The profiles are nearly identical and agree very well with the law of the wall (not shown) indicating that the flow at this location is unaffected by either wedge. Figure 2(b) shows that the mean profile of the highly accelerated boundary layer is much thinner than the upstream boundary layer and that the 2-D profile is more full than the 3-D profile.

Profiles of the fluctuating longitudinal velocity are shown in Fig. 3. Figure 3(a) shows that the boundary layer upstream of the wedge has the typical turbulent profile shape. There is a slight but unimportant difference between the 2-D and 3-D profiles. The longitudinal fluctuations in the accelerated boundary layer, shown in Fig. 3(b), have been damped significantly indicating the relaminarization process is underway. The 2-D and 3-D profiles are nearly identical in the region y(cm)<0.5. However, the 3-D profile has significantly larger (up to 2.5 times larger) values of $\sqrt{\overline{u'u'}}/U$ in the region $0.5<y$(cm)<3.

The differences between the 2-D and 3-D cases indicate that the Reynolds stress tensor has evolved differently in the two cases. The more full nature of the 2-D mean profile suggests that the Reynolds shear stress, $\overline{u'v'}$, is larger in the 2-D case for the region $0.1<y$(cm)<0.5, approximately. Fig-

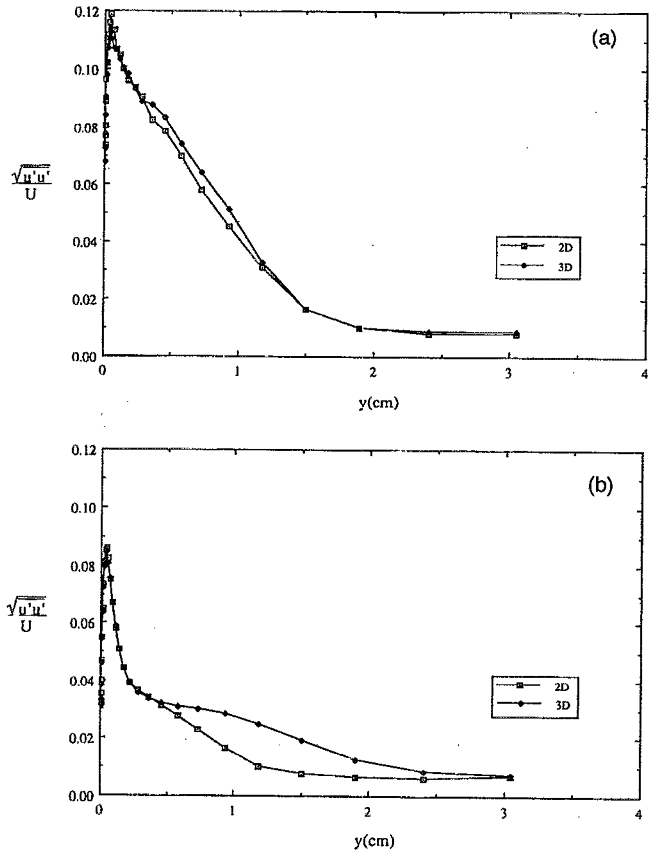

FIG. 3. Profiles of the root mean square of the longitudinal velocity fluctuations at 15.2 cm (a) upstream and (b) downstream of the leading edge of the wedge.

ure 3(b) shows that the longitudinal fluctuations are nearly identical in this region, thus the turbulent kinetic energy is likely to be the same for the two cases. This is consistent with previous observations in 3-DTBLs, where the shear stress is attenuated relative to the turbulent kinetic energy. Hence, for the 3-D wedge, the mean velocity profiles suggest that the shear stress, $\overline{u'v'}$ is smaller for $y(\mathrm{cm})<0.5$ and the measurements show that the normal stress, $\overline{u'u'}$, is larger for $y(\mathrm{cm})>0.5$, relative to the 2-D wedge flow. Thus, although the components of the Reynolds stress tensor are coupled in accelerating 2-D boundary layers, the spanwise flow apparently causes a decoupling in accelerating 3-DTBLs.

In order to understand the combined effects of three-dimensionality and high acceleration of a turbulent boundary layer, the full Reynolds stress tensor should be measured for this or a similar flow. Nevertheless, the measurements presented here suggest that while the acceleration is working to relaminarize the boundary layer, the cross-flow causes the Reynolds stress tensor components to decouple. In a recent review, Eaton[8] attributed the decoupling of the shear and normal stresses in 3-DTBLs without high streamwise acceleration to the interaction of the turbulent longitudinal vortex structure near the wall with the cross-flow which acts to suppress the turbulent ejections and sweeps. Measurements quantifying the interaction of the acceleration and cross-stream flow with the low- and high-speed streaks and quasistreamwise vortices in the near-wall region would augment the turbulent structure observations for nonaccelerating 3-DTBLs. Such measurements would also solidify our understanding of the role of turbulent structure in the relaminarization processes.

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