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Measurements of Turbulent Flow Structure in Supersonic Curved Wall Boundary Layers

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Introduction

THE underlying physics of high-speed flow over many of the shapes encountered on the interior surfaces of an engine are not well understood.[1,2] Thus, further experimental and related computational investigations are required to ascertain accurate predictions of the flow dynamics. The present paper discusses the results from an experimental study that examined energy spectral data and instantaneous (10 ns) Mie-scatting flow visualizations to quantify the effects of wall curvature on the large-scale turbulent boundary-layer flow structures for the curved wall configurations of Ref. 3. The pressure-gradient strength for high-speed flow is difficult to characterize.[2] Luker et al.[3] present a detailed discussion on pressure-strength characterization for the present curved wall models.

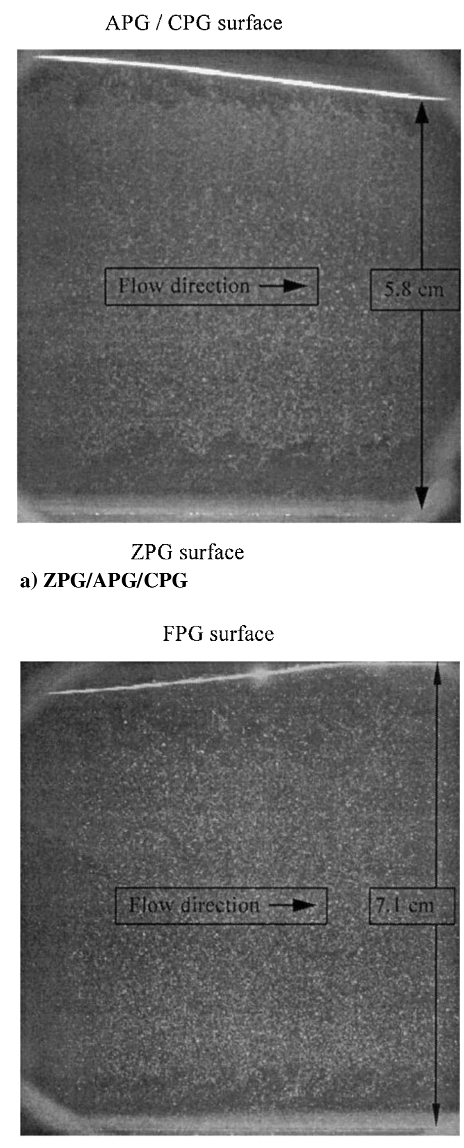
Facilities and Instrumentation

The tests were performed on the models and in the supersonic wind tunnel described by Luker et al.[3] The freestream Mach number was 2.8. The plenum chamber total pressure and total temperature were maintained at 0.219 ± 0.012 MPa and 295 ± 2 K, respectively. Luker et al.[3] have also shown the flowfield to be two dimensional for the current wind-tunnel models; hence, the present measurements were obtained along the tunnel centerline. The spectral measurements were acquired at the axial locations where previous laser Doppler velocimetry (LDV) data[3] were acquired, and the transverse locations were normal to the wall. The hot-wire instrumentation and procedures used here are described by Wier et al.[4]

A digital two-color particle image velocimetry (PIV) system was used for Mie-scattering flow visualization and preliminary PIV measurements.[5] The flow was seeded with triethylene-glycol smoke particles generated with a Dantec fog generator, where the polydisperse particles were confirmed to be less than 1.0 μm. Comparisons of preliminary PIV results with previous LDV results were performed to assess the flow tracking ability of the seed particles.[4] Even though the agreement with the LDV data was very good, the PIV velocity and turbulence intensity results were considered qualitative because of small sample sizes. Hence, only the instantaneous (10 ns) Mie-scattering images are described here.

Results and Discussion

The zero-pressure-gradient (ZPG), boundary-layer, large-scale turbulent flow structures visible in the boundary layers along the bottom walls shown in both Figs. 1a and 1b had inclination angles between 45 and 60 deg, which were similar to the results discussed by Spina,[6] and the structures spanned approximately one-half the boundary-layer thickness. Application of the adverse-pressure gradient (APG) (top wall, Fig. 1a) caused a decrease in the boundary-layer thickness and a reduction in the structure inclination angle (20–30 deg), where here the structures appeared to have spanned nearly the entire boundary layer. As the flow continued into the favorable-pressure-gradient region of this wall model, defined here as the combined-pressure-gradient (CPG) region, the boundary-layer thickness, the structure size and the structure angles began to grow in the x direction.



a) ZPG/APG/CPG

b) ZPG/FPG flow visualization

Fig. 1 Mie-scattering (PIV) flow visualizations.

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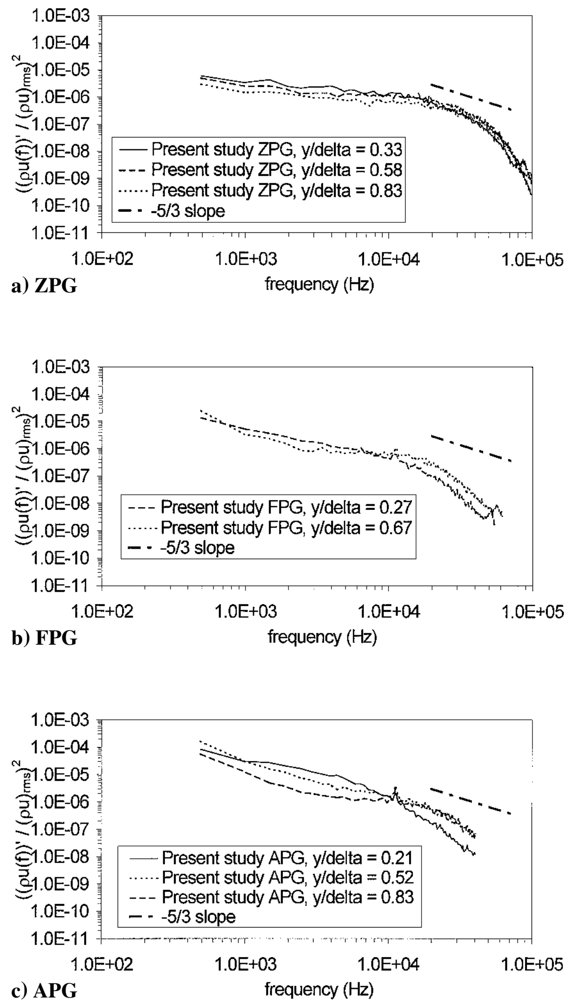

Fig. 2 Energy-spectra plots (uncertainty 7%).

The favorable-pressure-gradent (FPG) (top wall, in Fig. 1b) boundary layer grew in the streamwise direction, as expected. In addition, a higher population of small-scale structures was evident near the FPG boundary-layer edge, and the large-scale structures were not as clearly visible as for the ZPG boundary layers. This is consistent with the theory that a FPG promotes the dissociation of large-scale structures into small-scale structures.[3]

Figure 2a presents the energy-spectra data for $y/\delta = 0.33$, 0.58, and 0.83 for the ZPG flow. The ZPG data indicate that the energy spectrum was relatively flat for frequencies < 20 kHz (i.e., corresponding to the larger scale eddies) at all three boundary-layer locations. The near-wall trace showed a slightly higher dissipation rate in the range of 20–40 kHz.

Figure 2b presents the energy spectra for the FPG flow for $y/\delta =$ 0.27 and 0.67. The overall normalized levels shown in Fig. 2b were similar to those in Fig. 2a. However, $(\rho u')^2_{\mathrm{rms}}$ was roughly 50% lower for the FPG flow as compared to the ZPG flow. Hence, the dimensional values were significantly lower for the FPG, which was the expected stabilizing result.[1] A second distinguishing feature in Fig. 2b is the relatively large dropoff, compared to the ZPG flow, in the energy-spectra curve in the 0.5–10 kHz frequency range. This effect appeared to be more profound for the $y/\delta = 0.67$ trace, where the slope had a larger magnitude in the 0.5–3 kHz range as compared to the $y/\delta = 0.27$ trace. Also at the higher frequencies (> 10 kHz), the turbulent eddies in the outer region ($y/\delta = 0.67$) contained more energy. These two observations indicated an increased energy transfer from the large-scale structures to the small scales in the outer region of the boundary layer. Nearer to the wall, the boundary layer was less populated with large-scale structures; hence, the buildup of energy due to the FPG effects was less. This conclusion is consistent with the observation from the Mie-scattering image (Fig. 1), where it was noted that the large-scale structures were not as apparent.

Figure 2c presents the energy-spectra trace for the APG model for $y/\delta = 0.21$, 0.52, and 0.83. At the low frequencies (0.5 kHz), the APG energy levels were an order of magnitude larger than those of the ZPG flow, and $(\rho u')^2_{\mathrm{rms}}$ was roughly 45% larger for the APG as compared to the ZPG. Thus, the amplification was actually larger than that indicated in Fig. 2c. This result is consistent with the elongated large-scale structures visible in Fig. 1b and the destabilizing phenomena discussed by Spina et al.[2] As was the case for the FPG flow, the energy spectra for the APG flow also showed a relatively large dropoff in the frequency range of 0.5–10 kHz. Again, the effect was most pronounced in the outer region, and the near-wall trace exhibited a larger decay rate at the higher frequencies. Similar to the FGP flow, the trends in Fig. 2c indicated that the APG had the effect of increased energy transfer to the higher frequency (smaller scale) structures as compared to the ZPG case. The main difference between the APG and FPG results was the increased APG energy levels in the lower frequencies (< 3.0 kHz).

The trends in Figs. 2b and 2c coupled with the unchanged nature of the velocity profiles[3] indicated that increased lower frequency turbulent energy was not being transferred back to the mean flow, where much fuller velocity profiles would result. Instead, it is expected that the viscous dissipation increased for both the FPG and APG cases.

Conclusions

An experimental study of the turbulent flow structure for high-Reynolds number ($Re/m = 20 \times 10^6$) supersonic (Mach 2.8) boundary layers over curved walls was performed. The experimental techniques included hot-wire anemometry and Mie-scattering flow visualization. In general, the results of this study describe the impact of streamline curvature-driven FPGs and APGs on the spatial and temporal structure of the turbulent motion; these results are of both practical and theoretical interest.

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