Turbulent Compressible Three-Dimensional Mean Flow Profiles

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Theme

A CHALLENGING problem facing theoretical fluid dynamicists today is the prediction of the growth and development of compressible three-dimensional transitional/turbulent boundary layers. Cross-flow pressure gradients which maintain flow components in the lateral direction are found on virtually all proposed aeronautical flight vehicles. Several numerical[1,2] and integral[3,4] three-dimensional compressible turbulent boundary-layer calculation methods have been developed; however, there is a very limited amount of compressible three-dimensional turbulent boundary-layer data available for use as test cases (e.g., Refs. 5, 6), in contrast to incompressible flow. This paper presents the first detailed developing three-dimensional compressible transitional/turbulent boundary-layer profile test case to check out, develop, and improve the accuracy of the numerical and integral calculation methods.

Contents

The tests were conducted in the Mach 20 leg of the Langley High Reynolds Number Helium Facility, which has an axisymmetric contoured nozzle and a 1.525-m-diam test section. Boundary-layer pitot and hot-wire surveys (for mean mass flow, total temperature, and flow angularity data) were made at four axial stations (five axial stations for the windward ray) and five circumferential stations ($\phi = 0°$, 22.5°, 45°, 67.5°, and 90°) on a 1.525-m long, 2.87° half-angle sharp cone at $\alpha = 3.5°$. In addition to the pitot and hot-wire surveys, other data obtained included oil flow studies for determining surface streamline direction, surface heat transfer (from which the locus of boundary-layer transition was determined), wall static pressure for reducing the pitot data, and spark schlieren photographs delineating boundary-layer flow structure. The tests were conducted in unheated flow ($T_{t,\infty} \simeq 300°K$), with $T_w/T_{t,\infty} \simeq 1.0$ at a Reynolds number of $R_\infty/m = 33.4 \times 10^6$. Details of pitot and hot-wire probe construction and data accuracy, corrections, and analysis are discussed in Ref. 7. A unique swept, dual coil hot-wire probe was used to measure flow angularity through the boundary layer. The hot wire was used for measuring mean flow profiles in order to evaluate and compare this concept directly with the conventional pitot probe technique. Tabulated values of pertinent boundary-layer parameters and density, velocity (longitudinal and crossflow), crossflow angle, and pitot profile data are presented for all survey stations in Ref. 7.

Measured local flow angles in the boundary layer along the $\phi = 45°$ and $\phi = 90°$ ray for each of the four survey stations ($x/L = 0.365$ to 0.892) are presented in Fig. 1. Fairings were were made through the flow angularity data. Observe the large crossflow angles and the near-wall constant flow angle regions suggested by the data, which make this test case a stringent one. The flow angularity measurements illustrate the decreased crossflow with increasing surface distance (x/L) which is characteristic of an increasingly transitional flow. Because of the physical size of the probe, accurate angularity measurements were not obtained near the wall. The fairings in the near wall region were influenced by the surface oil flow-limiting streamline measurements so that at $y/\delta = 0$ the fairings were matched with the local wall flow. Note that most of the crossflow occurs in the inner 20%–30% of the boundary layer.

Crossflow velocity profiles for the last axial survey station are presented in Fig. 2. These crossflow profiles resemble the simple parabolic shape suggested by Mager[8] for incompressible flow. The degree of crossflow increases steadily with circumferential position, as expected from the local flow angle measurements.

Longitudinal velocity profile data for two circumferential angles, $\phi = 0°$ (windward ray) and $\phi = 90°$, are presented in a law of the wall form in Fig. 3a and 3b, where Danberg's[9] method is used to transform the present data to incompressible

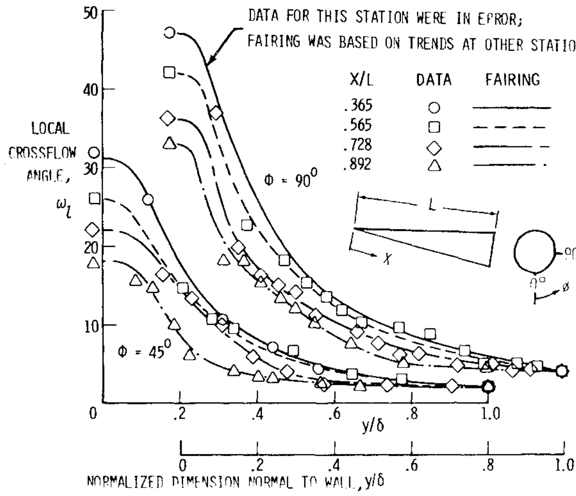

Fig. 1 Measured local crossflow angles at $\phi = 45°$ and 90°.

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Index categories: Boundary Layer and Convective Heat Transfer—Turbulent; Boundary-Layer Stability and Transition.

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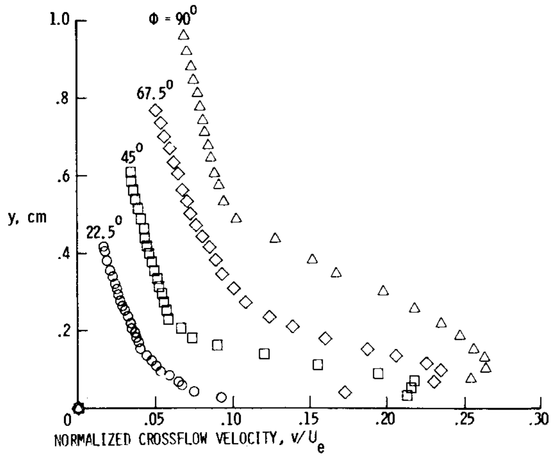

Fig. 2 Crossflow velocity profiles at survey station 4 ($x/L = 0.892$).

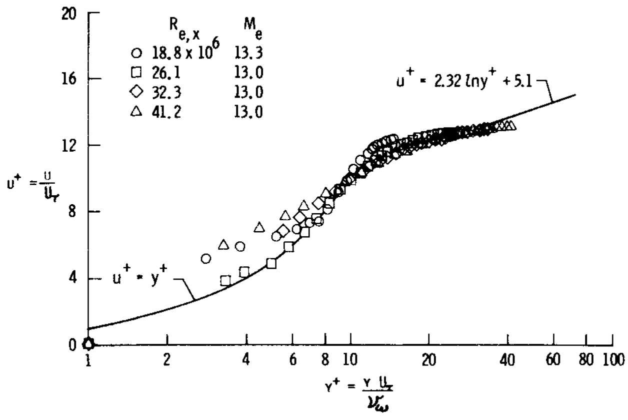

Fig. 3b Transformed longitudinal velocity profiles: $\phi = 90°$.

form. The transformed data suggest that the longitudinal velocity profile is quasi-two-dimensional. The velocity profile at the first station on the windward ray (Fig. 3a) appears nearly laminar except for a transitional like outer region, even though transition at the wall occurs downstream, between stations 3 and 4 (Ref. 7). This transitional outer profile structure ahead of wall transition further supports the precursor effect reported by Fischer.[10] Progressing longitudinally down the cone, the flow becomes increasingly transitional in structure (Fig. 3a). In comparison, for $\phi = 90°$ (Fig. 3b), the state of the boundary layer varies from moderately transitional to highly transitional along the four survey stations presented. This is to be expected since the wall transition location moves upstream with increasing circumferential angle.[7] The end of transition on the wall, determined by heat-transfer measurements,[7] always occurred off the end of the model. The filled symbols in the sublayer region ($y^+ < 10$) represent data obtained within one probe height of the wall and probably are in error due to probe interference effects. Mean profiles determined from hot-wire data are not shown, but generally show good agreement with the pitot-mean profile results.[7]

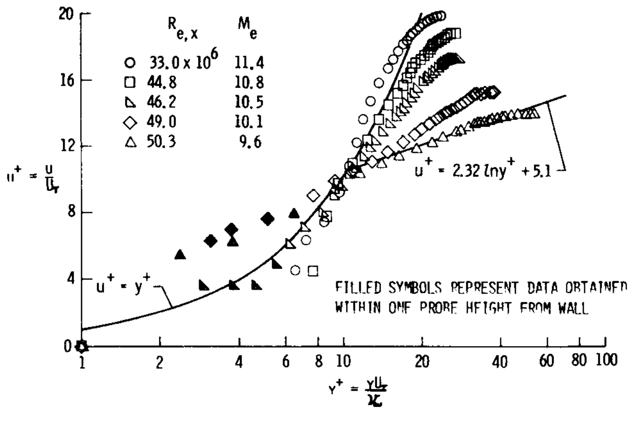

Fig. 3a Transformed longitudinal velocity profiles: $\phi = 0°$ (windward ray).

Because of the high Mach number and "low Reynolds number" (maximum $R_{e,\theta} \approx 1500$) conditions of the present flow, a thick sublayer exists, with $\delta_{\text{S.L.}} | \delta \approx 0.2$. The present results represent the first data obtained in the sublayer of a compressible, three-dimensional transitional/turbulent boundary layer and the "low Reynolds number," hypersonic, large crossflow conditions make these data a challenging stringent test case for the analytical prediction methods.

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