Pressure-Gradient Effects on Hypersonic Turbulent Skin-Friction and Boundary-Layer Profiles

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Theme

LOCAL skin friction, total-temperature profiles and Pitot-pressure profiles were measured in air on the wall of a Mach 7.4 wind tunnel. Measurements were made at a single station located in the test section about 10 m downstream of the strong favorable pressure gradient of the nozzle throat. Measured results are compared with those predicted by a finite-difference method programed by H. Dwyer et al.[1] This method is based on eddy-viscosity assumptions used in the Cebeci method except for omission of the intermittency factor for the outer part of the boundary layer, the effect of which was found to be small. Basic equations are given in the preprint on which this synoptics is based and in Ref. 1. Additional remarks regarding formulation of this method may be found in Appendix A of Ref. 2.

Content

Wall-temperature ratio (T_w/T_{aw}) was varied from 0.32 to 0.47 by changing the total temperature of the wind tunnel from 1044° to 707°K. Reynolds number (Re_x) was varied from 15 to 134 million by changing the tunnel pressure and temperature. Re_x was based on the distance from the wind-tunnel throat to the measuring station (10.1 m) and the stream unit Reynolds number at that station. For the calculations, the boundary layer was assumed to be turbulent from the throat to the measuring station and to exist over an isothermal wall; however, check calculations for typical nonisothermal wall conditions gave only small differences at the measuring station.

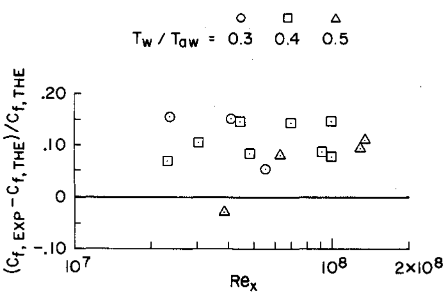

Fig. 1 Predictions of skin friction by finite-difference method, $M_e = 7.4$.

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Index categories: Boundary-Layers and Convective Heat Transfer—Turbulent; Supersonic and Hypersonic Flow; Nozzle and Channel Flow

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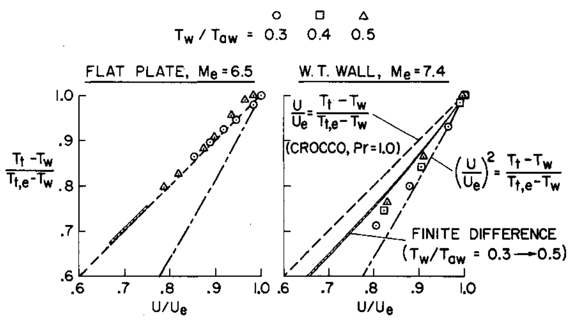

Fig. 2 Temperature profiles.

In Fig. 1 the difference between the experimental and theoretical skin friction is shown to be little affected (within experimental accuracy in C_f of $\pm 5\%$) by either changes in Reynolds number or wall-temperature ratio. In general, the skin friction was underpredicted by less than 15%, the same percentage as found for the same method applied to a flat plate in the same facility.[2]

Temperature profiles are shown in Fig. 2 for the flat-plate data of Ref. 3 and the wind-tunnel wall data of this investigation. For the flat plate, the data lie close to the linear curves representing both the finite-difference and Crocco distributions; however, for the wind-tunnel wall, the data for all wall-temperature ratios lie generally between the finite-difference and quadratic curves. For the wind-tunnel wall, choice of the initial temperature profile for the finite-difference program being that of Crocco or a quadratic did not affect the calculated temperature distribution at the measuring station, suggesting that the dominant factor in producing a nonlinear distribution was the strong pressure gradient near the throat. Similar results are reported in Refs. 4 and 5.

In Fig. 3 a representative Mach number and velocity profile is shown for each wall-temperature ratio. The Mach-number profiles are predicted to be somewhat thicker and less full than measured; whereas velocity profiles are adequately predicted.

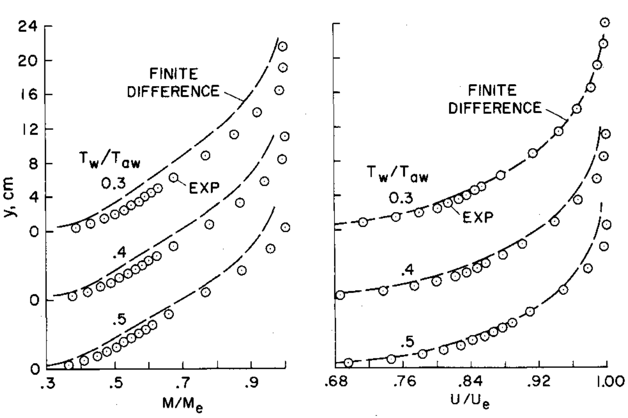

Fig. 3 Mach number and velocity profiles, $M_e = 7.4$.

Evidently, the good agreement for the velocity profiles is probably a result of compensating effects from the finite-difference program underpredicting the Mach number and overpredicting the temperature since $U \sim M(T)^{1/2}$.

Finally, it was found that the velocity profile exponent $1/N$ as defined by $U/U_e = (y/\delta)^{1/N}$ decreased from about $\frac{1}{7}$ to $\frac{1}{9}$ with increasing Reynolds number in accordance with predicted values from the finite-difference method and experimental values from incompressible and supersonic profiles. Some data in previous experiments[2] at lower Reynolds numbers ($Re_\theta < 7 \times 10^3$) and hypersonic Mach numbers exhibit much higher N's than 7. Therefore, considerable care should be exercised in interpreting such results which are evidently for nonequilibrated flow and, therefore, not representative of fully developed turbulent boundary-layer flow. It should be emphasized, however, that skin friction which is related mainly to the inner part of the boundary layer was predicted[2] within 10% by the Van Driest method (II) on the basis of the measured Re_θ for those profiles having abnormally high values of N.

References

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[3] Hopkins, E. J., Keener, E. R., and Louie, P. T., "Direct Measurements of Turbulent Skin Friction on a Nonadiabatic Flat Plate at Mach Number 6.5 and Comparison with Eight Theories," TN D-5675, 1970, NASA.

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