A High Mach Number Turbulent Boundary-Layer Study

E. Backx* and B.E. Richards†
von Karman Institute for Fluid Dynamics, Rhode Saint Genese, Belgium

Theme

MEASUREMENTS were made in a Mach 15 and 19.8 cold-wall turbulent boundary layer developed on the wall of the conical nozzle of the von Kármán Institute (VKI) Longshot free piston tunnel. This tunnel has the unique capability to generate a high Mach number at a high Reynolds number in nitrogen ($M=15$, $Re_\theta=34{,}600$, where θ is momentum thickness, $T_w/T_0=0.15$; $M=19.8$, $Re_\theta=24{,}300$, $T_w/T_0=0.11$). The experimental profiles are used to compute the turbulent shear stress and heat flux profiles using the averaged boundary-layer equations. From these, the mixing length and eddy viscosity profiles are derived. A similar technique has been used in Refs. 1-3.

More details of the present measurements can be found in the full paper and in Ref. 4. Experimental data for high hypersonic ($M>10$) turbulent boundary layers are available in Refs. 5-9. Most of these data[5-7] are for conditions of large heat transfer. References 8 and 9, which use helium as the test gas, also include measurements for nearly adiabatic wall conditions.

Contents

The tests were conducted in the Longshot hypersonic wind tunnel, a free-piston intermittent ($\cong 10$ msec flow duration) facility that uses nitrogen as the test gas. Fast response instrumentation has been used to make surveys of pitot pressure, stagnation temperature, and mass flow through the boundary layer. The measurements of stagnation temperature were made using a fine ($d=5$-10 μm) tungsten-wire resistance thermometer. A high length-to-diameter ratio ($L/d=900$) was chosen to keep conduction end loss corrections small. The static pressure measured on the wall is much higher than the value calculated from the freestream Mach number and the reservoir pressure. Several investigators have reported such differences in static pressure. The results obtained with the mass flow probe suggest a decrease in static pressure from the wall value up to $y/\delta=0.6$. Reference 10 provides a recent review of possible causes. The pitot pressure profile and the stagnation temperature profile were obtained with good measurement repeatability, although the high breakage rate of the fine wires necessitated a large number of repeated tests at the same conditions. A quadratic variation of nondimensional enthalpy with nondimensional velocity was obtained, except that, near the wall, the data showed a tendency toward a linear profile.

In calculating the mixing length and eddy viscosity distribution from the time-averaged boundary-layer equations, the assumption is made that the mean flow quantities are all functions of only y/δ (δ based on the pitot profile). This assumption was verified by demonstrating profile similarity by taking measurements at two stations further upstream. The shear stress at the wall was not measured but was inferred from the measured heat transfer (using thin-film thermometry) at the wall, and assuming a value for the Reynolds analogy factor such that $\tau=0$ at $y/\delta=1$. The method of calculation was similar to that used in Ref. 3. The calculated distributions of mixing length and eddy viscosity fall within the band plotted in the data compilations of Figs. 1 and 2. In these figures, it is demonstrated that agreement with the currently used models and experiments is obtained close to the wall. Away from the wall, the calculated values compare favorably in trend with the results from Sturek[11] and Lee et al.,[2] obtained at lower Mach numbers, and which then serve to demonstrate that the models represented here overpredict the mixing length and eddy viscosity. The recent article by Bushnell et al.[12] based on a large number of data indicates for $y/\delta>0.5$ a value of $\ell/\delta=0.07$ for $\delta^+=2.10^3(\delta^+=u_{\tau,w}\delta/\nu_w)$ and δ based on 0.995, the freestream velocity. On the same basis, the present value for ℓ/δ would have the value of 0.05.

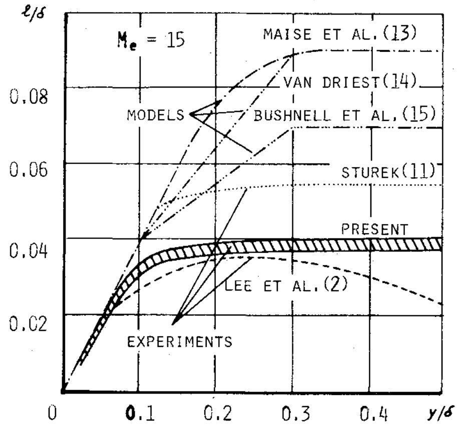

Fig. 1 Mixing length variation through the boundary layer.

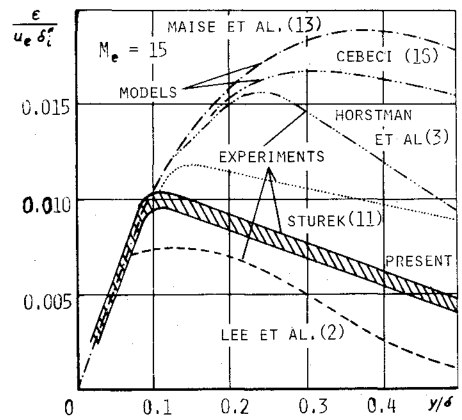

Fig. 2 Eddy viscosity variation through the boundary layer.

Received Nov. 13, 1975; synoptic received March 18, 1976. Full paper available from National Technical Information Service, Springfield, Va. 22151 as N76-22163 at the standard price (available upon request).

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

*Research Scientist, Aspirant NFWO; presently at the University of Louvain.

†Associate Professor. Member AIAA.

References

[1] Bushnell, D. M. and Morris, O. J., "Shear Stress, Eddy Viscosity and Mixing Length Distribution in Hypersonic Turbulent Boundary Layers," NASA TM X 2310, Aug. 1971.

[2]Lee, R. E. and Smith, R. A., "Evaluation of the Turbulent Transport Terms for a Two Dimensional Nozzle Wall Boundary Layer Flow at Mach 5 and with Pressure Gradient, Heat Transfer and Upstream Effects," AIAA Paper 74-96; revision published in *AIAA Journal*, Vol. 13, Feb. 1975, pp. 177-184.

[3]Horstman, C. C. and Owen, F. K., "Turbulent Properties of a Compressible Boundary Layer," *AIAA Journal*, Vol. 10, Nov. 1972, pp. 1418-1424.

[4]Backx, E., "Experimental Study of the Turbulent Boundary Layer at Mach 15 and 19.8 in a Conical Nozzle," von Karman Institute, TN 102, Aug. 1974.

[5]Scaggs, N. E., "Boundary Layer Profile Measurements in Hypersonic Nozzles," U. S. Air Force, ARL 66-041, July 1966.

[6]Perry, J. H., "An Experimental Study of the Turbulent Hypersonic Boundary Layer at High Rates of Wall Heat Transfer," Ph.D. Thesis, Univ. of Southampton, 1968.

[7]Beckwith, I. E., Harvey, W. D., and Clark, F. L., "Comparisons of Turbulent Boundary Layer Measurements at Mach Number 19.5 with Theory and an Assessment of Probe Errors," NASA TN D 6192, June 1971.

[8]Fisher, M. C., Maddalon, D. V., Weinstein, L. M., and Wagner, R. D., "Boundary Layer Pitot and Hot Wire Surveys at $M \simeq 20$," *AIAA Journal*, Vol. 9, May 1971, pp. 826-834.

[9]Kemp, J. H. and Owen, F. K.,"Experimental Study of Nozzle Wall Boundary Layers at Mach 20 to 47," NASA TN D 6965, Oct. 1972.

[10]Fernholz, H. H. and Finley, P. J., "A Critical Compilation of Compressible Turbulent Boundary Layer Data," *Lecture Series 86 on Compressible Turbulent Boundary Layers,* von Karman Institute, March 1-5, 1976.

[11]Sturek, W. B., "Calculation of Turbulent Shear Stress in Supersonic Turbulent Boundary Layer Zero and Adverse Pressure Gradient Flow," AIAA Paper 73-166; revision published in *AIAA Journal*, Vol. 12, March 1974, pp. 375-376.

[12]Bushnell, D. M., Cary, A. M., and Holley, B. B., "Mixing Length in Low Reynolds Number Compressible Turbulent Boundary Layers," *AIAA Journal,* Vol. 13, Aug. 1975, pp. 1119-1121.

[13]Maise, G. and McDonald, H., "Mixing Length and Kinematic Eddy Viscosity in a Compressible Boundary Layer," *AIAA Journal,* Vol. 6, Jan. 1968, pp. 73-80.

[14]Van Driest, E. R., "On Turbulent Flows Near a Wall," *Journal of the Aeronautical Sciences*, Vol. 23, Nov. 1970, pp. 1007-1011.

[15]Bushnell, D. M. and Beckwith, I. E., "Calculation of Nonequilibrium Hypersonic Turbulent Boundary Layers and Comparisons with Experimental Data," *AIAA Journal*, Vol. 8, Aug. 1970, pp. 1462-1469.

[16]Cebeci, T., "The Behavior of Turbulent Flow Near a Porous Wall with Pressure Gradient," *AIAA Journal*, Vol. 8, Dec. 1970, pp. 2152-2156.