Technical Notes

TECHNICAL NOTES are short manuscripts describing new developments or important results of a preliminary nature. These Notes cannot exceed 6 manuscript pages and 3 figures; a page of text may be substituted for a figure and vice versa. After informal review by the editors, they may be published within a few months of the date of receipt. Style requirements are the same as for regular contributions (see inside back cover).

Compressible Turbulent Boundary Layer in Strong Adverse Pressure Gradient

Dong-Ho Lee*
Korea Advanced Institute of Science and Technology
Seoul, Korea

Introduction

SINCE the first proposal of a boundary-layer concept by Prandtl in 1904, a number of theoretical and experimental studies have been made. Recent developments in computational methods make it possible to predict the behavior of the incompressible turbulent boundary layer for arbitrary pressure gradient distributions in the absence of separation. However, in compressible flows compressibility effects and turbulence models that are under strong pressure gradient are not well defined.

An experiment of shock wave/turbulent boundary-layer interaction in a supersonic wind tunnel was reported by Ardonceau et al.[1] This Note summarizes an extensive analysis of the mean data carried out to study the effects of pressure gradient and upstream history on the development of compressible turbulent boundary layer.

Data Analysis

A compression corner model was used to study the shock wave/boundary-layer interaction at a freestream Mach number M_∞ of 2.25. The stagnation temperature was controlled to obtain an adiabatic wall condition and the resulting Reynolds number was 1.1×10^7 m^{-1}. The data with 13 and 18 deg corner angles are analyzed here, as these angles correspond to the incipient separation and distinct separation bubble, respectively.

The distributions of wall pressures are presented in Fig. 1 along with a sketch of compression corner installed in the wind tunnel. A slight decrease of pressure after reaching maximum value is probably due to three-dimensional effects in the wind tunnel, so that data with negative pressure gradients are excluded. For consistency of measurement, the velocity component parallel to the nozzle axis was measured by laser Doppler velocimeter in a plane perpendicular to the nozzle axis. The original data were divided by $\cos\alpha$ to give the velocity parallel to the compression corner surface. Then the velocity profiles in the plane normal to the wall surface are obtained by interpolation.

Fernholz and Finley[2] found that the modified Crocco relation of Eq. (1) is a reasonable first-order approximation for the temperature-velocity relationship of a compressible turbulent boundary layer with pressure gradients in the stream direction along adiabatic walls,

$$\frac{\bar{T}}{T_e}=1+r\frac{\gamma-1}{2}M_e^2\left[1-\left(\frac{\bar{U}}{U_e}\right)^2\right] \tag{1}$$

where r is the recovery factor and the subscript e indicates values at boundary-layer edge. The values of density are obtained from the equation of state by using the calculated temperature and measured static pressure.

Maise and McDonald[3] and Lewis et al.[4] found general agreement between incompressible theory and measurements of supersonic flows through the van Driest transformation which was used to account for compressibility effects. The values of wall shear stress are determined from the curve-fitting procedure of Coles' composite wall-wake law assuming constant pressure. The profiles of transformed velocity $\bar{U}^*$ as seen in Fig. 2 are plotted in the law of the wall coordinates which is the most meaningful presentation method for incompressible turbulent boundary layers. In fact, a number of small compression waves were widespread in the outer part of the boundary layer and they resulted in a maximum pressure difference of 9%.

In Fig. 2, the Reynolds number given for each profile is defined as $\rho_e U_e \delta_2/\mu_w$ by using the viscosity at wall μ_w and the momentum loss thickness δ_2. This type of Reynolds number had been justified as the most representative parameter for compressible boundary layer in Ref. 2.

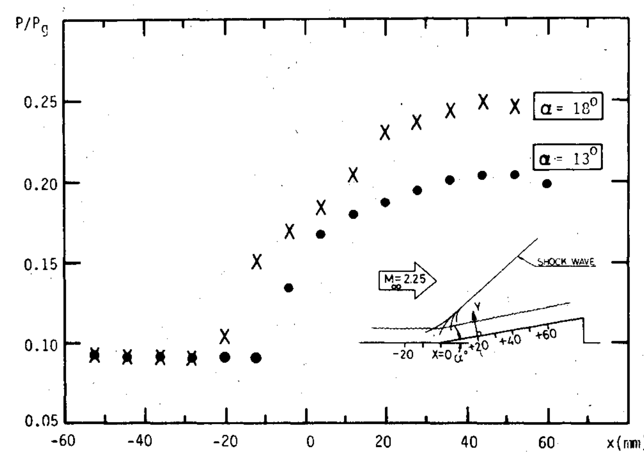

Fig. 1 Wall pressure distributions ($P_g = 0.9\times10^5$ N/m^2).

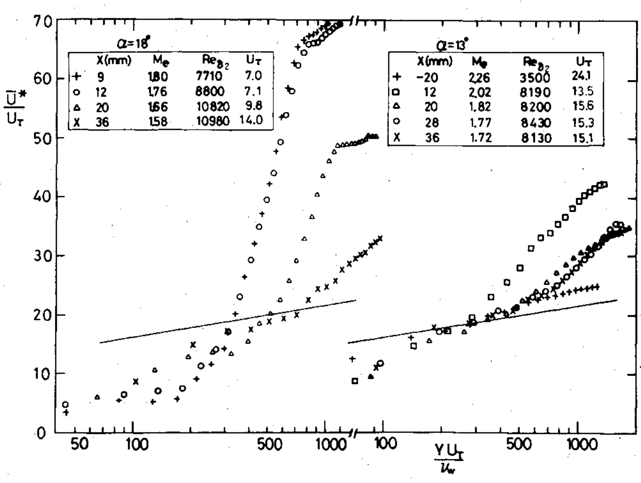

Fig. 2 Profiles of $\bar{U}^*/U_\tau$ vs yU_τ/ν_w (straight line indicates the law of the wall).

Received Jan. 4, 1982; revision received Aug. 30, 1982.

*Assistant Professor, Department of Aeronautical Engineering. Member AIAA.

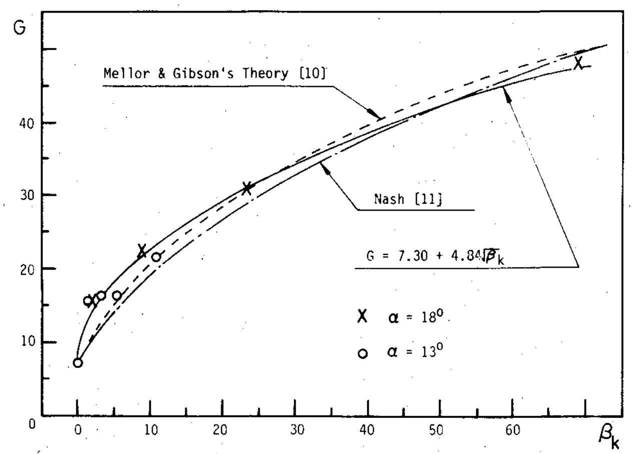

Fig. 3 Correlation of defect shape factor with pressure gradient parameter.

The defect shape factor G defined in Eq. (2) is generally used to show the effects of pressure gradient,

$$G=\int_0^{\delta}\left(\frac{U_e^*-\bar{U}^*}{U_\tau}\right)^2 \mathrm{d}\left(\frac{y}{\Delta}\right) \tag{2}$$

where the defect thickness Δ is defined as

$$\int_0^{\delta}(U_e^*-\bar{U}^*)/U_\tau \mathrm{d}y$$

The values of G are plotted in Fig. 3 against the compressible pressure gradient β_k, as suggested by Alber and Coats.[5]

Results and Discussions

In the above analysis, one may have reservations about the values of wall shear stress obtained with the assumption of a constant pressure boundary layer. But, considering the inevitable complexity of flowfield, the results as seen in Fig. 2 are encouraging in comparison with some direct measurements with a Preston tube[6] or with a heated-wire gage[7] in milder pressure gradient than this case:

1) The profiles of $\alpha=13$ deg (in Fig. 2) show a large increase in wake components as found in incompressible flows with an adverse pressure gradient. But the sublayer grows in relative thickness in contrast to the subsonic case. This fact was also noted in Ref. 2. When there exists a separation bubble ($\alpha=18$ deg), the profiles are mostly concave and have lower values than the law of the wall. So it could be said that the sublayer becomes thicker and covers a large part of the boundary layer downstream of the separation bubble.

2) Correlation of defect shape factor G with pressure gradient parameter β_k is obtained in the form of $G=7.30+4.84\sqrt{\beta_k}$ for $0<\beta_k<70$, as can be seen in Fig. 3. The maximum β_k is about 70, and such high values of β_k could not be found in similar analysis of compressible turbulent boundary layer. For example, the maximum β_k was 3.5 in Ref. 8, about 2 in Ref. 4, and 1.8 in Ref. 9. So the values of G are compared with the theory and experimental results of incompressible flow. The correlation obtained from the analysis shows good agreement with Mellor and Gibson's theory[10] for equilibrium incompressible flow and also with Nash's correlation[11] for incompressible flows.

References

[1]Ardonceau, P., Lee, D. H., de Roquefort, T. A., and Goethals, R., "Turbulence Behavior in a Shock-Wave/Boundary Layer Interaction," *Turbulent Boundary Layers—Experiments, Theory, and Modelling,* AGARD CP 271, 1979.

[2]Fernholz, H. H. and Finley, P. J., "A Critical Commentary on Mean Flow Data for Two-Dimensional Compressible Turbulent Boundary Layers," AGARDograph No. 253, 1980.

[3]Maise, G. and McDonald, H., "Mixing Length and Kinematic Eddy Viscosity in a Compressible Boundary Layer," *AIAA Journal,* Vol. 6, Jan. 1968, pp. 73-79.

[4]Lewis, J. E., Gran, R. L., and Kubota, T., "An Experiment on the Adiabatic Compressible Turbulent Boundary Layer in Adverse and Favourable Pressure Gradients," *Journal of Fluid Mechanics,* Vol. 51, Pt. 4, 1972, pp. 657-672.

[5]Alber, I. E. and Coats, D. E., "Analytical Investigation of Equilibrium Compressible Turbulent Boundary Layers," AIAA Paper 69-689, 1969.

[6]Peake, D. J., Brakmann, G., and Romeskie, J. M., "Comparisons between Some High Reynolds Number Turbulent Boundary Layer Experiments at Mach 4 and Various Recent Calculation Procedures," National Research Council of Canada and AGARD CP-93-71, 1971, Paper 11.

[7]Kussoy, M. I., Horstman, C. C., and Acharya, M., "An Experimental Documentation of Pressure Gradient and Reynolds Number Effects on Compressible Turbulent Boundary Layer," NASA TM 78488, 1978.

[8]Struek, W. B. and Danberg, J. E., "Supersonic Turbulent Boundary Layer in Adverse Pressure Gradient, Pt. II: Data Analysis," *AIAA Journal,* Vol. 10, May 1972, pp. 630-635.

[9]Laderman, A. J., "Adverse Pressure Gradient Effects on Supersonic Boundary Layer Turbulence," *AIAA Journal,* Vol. 18, Oct. 1980, pp. 1186-1195.

[10]Mellor, G. L. and Gibson, D. M., "Equilibrium Turbulent Boundary Layers," *Journal of Fluid Mechanics,* Vol. 24, Pt. 2, 1966, pp. 225-253.

[11]Nash, J. F., "Turbulent-Boundary-Layer Behavior and the Auxiliary Equation," AGARDograph 97, 1965, pp. 245-279.

Global Distribution of Stratospheric Aerosols by Satellite Measurements

M. P. McCormick*
NASA Langley Research Center, Hampton, Virginia

Introduction

IN the lower to middle stratosphere there exists a region of increased concentration of large particles greater than about 0.1-μm radius. This layer of large particles is called the stratospheric aerosol layer or Junge layer.[1] Therein, the mixing ratio reaches a peak at approximately 10 km above the local tropopause of about 6-10 particles/mg of air during nonvolcanic periods which corresponds to peak concentrations of about 0.5 particles/cm³ (Ref. 2). The size distributions for these particles generally are described by an analytical function chosen to fit a set of experimental data. A lognormal distribution seems to fit a large number of observations and agrees with many other size distribution functions for radii between 0.1 and 0.6 μm. This size region is the dominant contributor to stratospheric aerosol extinction and backscatter at red and near-infrared wavelengths.[3] The exact composition of the aerosol particles is not known but most evidence supports an aerosol composed of a 75% sulfuric acid and 25% water solution.[4] The primary source of sulfur that establishes the background layer is thought to be tropospheric OCS (carbonyl sulfide), but it is becoming less clear as to whether or not volcanoes are the primary source. In either case, gas phase H_2SO_4 is formed which then par-

Presented as Paper 82-0086 at the AIAA 20th Aerospace Sciences Meeting, Orlando, Fla., Jan. 11-14, 1982; submitted Jan. 22, 1982; revision received July 16, 1982. This paper is declared a work of the U.S. Government and therefore is in the public domain.

*Head, Aerosol Research Branch, Atmospheric Sciences Division.