Reynolds Number and Pressure Gradient Effects on Compressible Turbulent Boundary Layers

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Abstract

THE present study fills the current void in experimental data by presenting the results of a detailed investigation of attached supersonic turbulent boundary layers over an extensive Reynolds number range (12×10^6 to 314×10^6). Experimental measurements obtained for adverse pressure gradients ranging in magnitude from those of previous investigations[1] to those approaching separation are presented. The measurements include mean values of surface pressure and skin-friction, mean-flow profiles, and profiles of the three turbulent velocity fluctuation components and turbulent shear stress. These data were obtained in sufficient detail to completely document the flowfields from the upstream undisturbed equilibrium boundary layer through the pressure gradient region and for some distance downstream. The experimental results are compared with computations employing several turbulence models including two higher order models. The effects of pressure gradient and Reynolds number on surface skin friction are examined in detail. The fluctuating flow measurements are used to validate the details of the flowfield as predicted by the higher-order models. Finally, conclusions are drawn regarding the usefulness of the models in predicting compressible boundary layer flows with strong pressure gradients.

Contents

The experiment was conducted in the NASA Ames Research Center's high Reynolds number channel. The test configuration consisted of an axisymmetric supersonic nozzle and a constant diameter test section into which interchangeable axisymmetric contoured centerbodies could be inserted. Two bodies were chosen to impose pressure gradients on the turbulent boundary layer that developed on the test section wall. These centerbodies, designed for a medium and severe pressure gradient, resulted in adverse pressure gradients along the wall boundary layer with values of the nondimensional pressure gradient parameter ($p^+ = \rho_w \mu_w (\mathrm{d}p_w/\mathrm{d}x)/(\rho_w \tau_w)^{3/2}$) ranging from 0.003 to 0.123 over the Reynolds number range investigated. The present measurements were obtained on the test section wall in a region 280 to 300 cm downstream from the nozzle throat, sufficiently downstream to establish a fully developed equilibrium turbulent boundary layer along the tube wall. The nominal test conditions were $M_\infty = 2.3$; total and wall temperature, 278 K; wall boundary-layer thickness upstream of the interaction, 4 cm; and Reynolds number based on distance from the nozzle throat, $Re_{x0} = 11.7\times10^6$, 35.3×10^6, 105×10^6 and 314×10^6.

Surface pressure and skin-friction measurements were obtained for both centerbodies at four Reynolds numbers. Both mean and fluctuating flowfield surveys were obtained throughout the interaction region for the two centerbodies at a single Reynolds number, $Re_{x0} = 35.3\times10^6$. Velocity, density, and pressure profiles were obtained from pitot and static pressure and total temperature surveys. The three fluctuating velocity components and turbulent shear stress profiles were obtained using single hot-wire and dual hot-film probes. The details of the experimental procedures and data reduction as well as a complete tabulation of all the data presented in this article are included in Ref. 2.

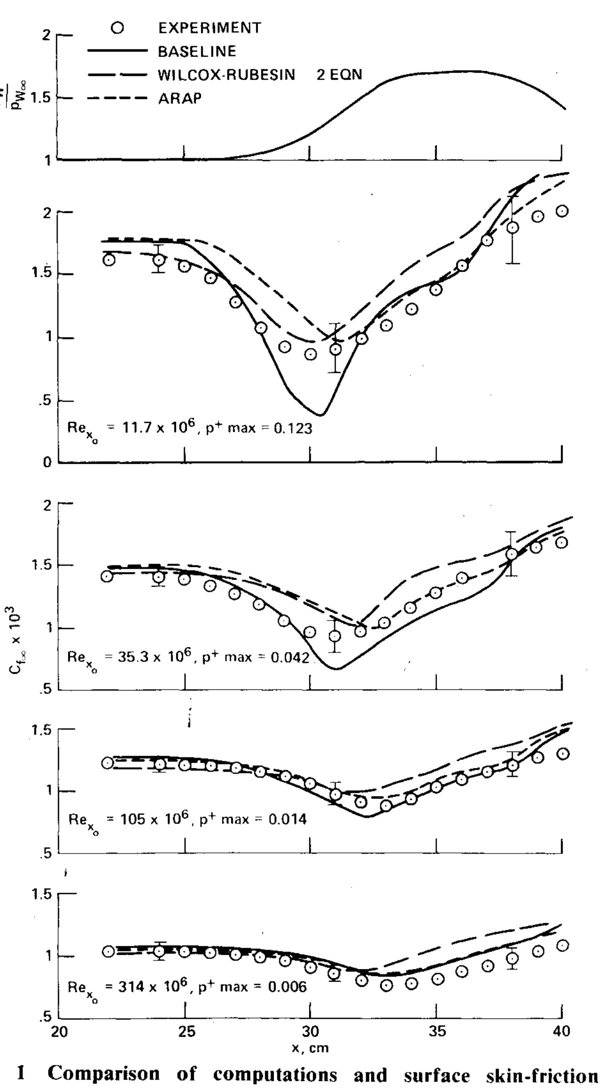

Fig. 1 Comparison of computations and surface skin-friction measurements at four Reynolds numbers, centerbody *B*.

Presented as Paper 78-199 at the AIAA 16th Aerospace Sciences Meeting, Huntsville, Ala., Jan. 16-18, 1978; submitted Feb. 8, 1978; synoptic received June 29, 1978. Full paper available from AIAA Library, 750 Third Avenue, New York, N.Y. 10017. Price: Microfiche, $2.00; hard copy, $5.00. **Order must be accompanied by remittance.** Copyright © American Institute of Aeronautics and Astronautics, Inc., 1978. All rights reserved.

Index categories: Boundary Layers and Convective Heat Transfer—Turbulent; Computational Methods; Supersonic and Hypersonic Flow.

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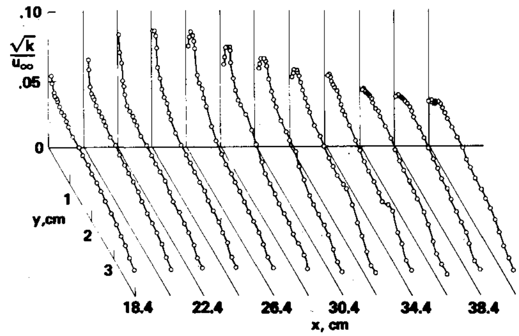

Fig. 2 Turbulent kinetic energy profiles across the flowfield, centerbody *B*, $Re_{x0} = 35.3 \times 10^6$.

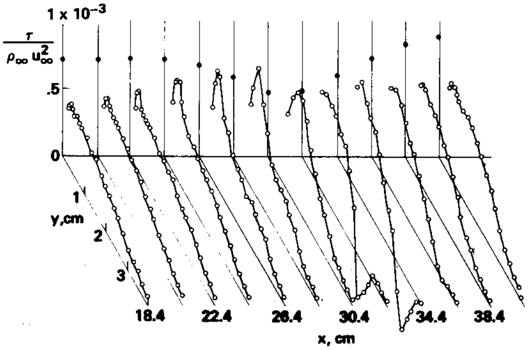

Fig. 3 Turbulent shear stress profiles across the flowfield, centerbody *B*, $Re_{x0} = 35.3 \times 10^6$.

The two flowfields described above have been computed with the boundary-layer equations using three turbulence models. The three models employed were the baseline, Wilcox-Rubesin, and ARAP models. The baseline model is the standard two-layer algebraic eddy-viscosity model developed by Cebeci and Smith.[3] The Wilcox-Rubesin model is a complete two-equation, eddy-viscosity turbulence model recently developed for compressible flow. This model is an improved version of the Wilcox-Traci model[4] with modifications to the turbulence mixing energy equation. The ARAP model is a full Reynolds stress model which for compressible flow leads to a system of 12 partial differential equations.[5] A detailed discussion of these models is included in Ref. 1. In the following comparisons, no special adjustments to the modeling coefficients were made to force agreement of the computations with the experimental data.

The experimental values of surface skin friction and wall pressure at four Reynolds numbers are compared with the results from three prediction methods for centerbody *B* in Fig. 1. The nondimensional pressure distribution was essentially independent of Reynolds number; thus, only one average curve is shown. The skin-friction data represent average values with appropriate scatter bars for the basic uncertainties in the measured quantities. The maximum value of the nondimensional pressure gradient parameter p^+ is indicated for each Reynolds number tested. Previous investigations only included values up to 0.012. We can note several things about the skin-friction data. As expected, the initial value of C_{f_∞} decreases as Reynolds number increases. At the lowest Reynolds numbers the data show the most streamwise variation in skin-friction and at the highest-Reynolds numbers there is very little streamwise variation. In general the computations employing the various turbulence models predict the experimental Reynolds number and pressure gradient effects over the complete range of test variables. The baseline model results underpredict the minimum values of skin-friction at the lowest Reynolds numbers but when a pressure gradient correction[3] is applied the agreement with the data is improved.[6] The Wilcox-Rubesin model slightly overpredicts the measured values in the downstream portion of each flow.

Turbulent kinetic energy and shear-stress profiles at $Re_{x0} = 35.3 \times 10^6$ are shown for centerbody *B* in Figs. 2 and 3. The solid symbols in Fig. 3 represent the wall shear measurements shown in Fig. 1. These profiles clearly show the effects of both adverse and favorable pressure gradients. The adverse gradient increases both the kinetic energy and shear stress in the flowfield while the wall shear decreases. The effect of the favorable gradient is opposite. Detailed comparisons between these data and the computed results and similar comparisons for the other centerbody tested are contained in the full paper.

Compressible boundary-layer flows, with adverse pressure gradients of varying degrees of severity, were experimentally investigated over a wide range of Reynolds numbers. The data were of sufficient detail and quality to permit the appraisal of the validity of various turbulence models used for calculating these flows. For the first time all three components of the fluctuating velocities as well as turbulent shear stress have been measured for compressible pressure gradient flows. Computations, employing several turbulence models, were compared with these data. Generally, the performance of the higher order models is independent of the magnitude of the pressure gradient and Reynolds number and should be sufficient for engineering calculations in attached boundary-layer flows.

References

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