Computation of Three-Dimensional Turbulent Separated Flows at Supersonic Speeds

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Abstract

NUMERICAL solutions of the time-averaged Navier-Stokes equations employing an algebraic eddy-viscosity model have been obtained for three-dimensional turbulent flowfields at supersonic speeds. The computed results are compared with a series of experimental test flows describing the interaction of a swept shock wave with a turbulent boundary layer for various shock-wave strengths. The experimental results of Oskam et al.[1] and Peake[2] were chosen for comparisons. These experiments represent the two most thoroughly documented flows of this type, in that detailed streamwise and transverse velocity profiles as well as surface pressure, skin friction, and heat transfer were obtained throughout the interaction region for several Mach numbers and shock-wave strengths. The experimental cases extend from nonseparated to highly three-dimensional "separated" flows. Excellent agreement is obtained between the computed and experimental surface and flowfield results.

Contents

The governing equations of the present analysis are the time-dependent, compressible, three-dimensional Navier-Stokes equations cast in terms of mass-averaged variables, with the bulk viscosity and the specific turbulent energy in the normal stress components omitted. Turbulent closure is accomplished by expressing the Reynolds stress tensor in terms of the product of an eddy viscosity with the mean velocity gradients. Also, a turbulent Prandtl number is used for the Reynolds heat flux. The resulting equations are described in Refs. 3 and 4.

The computation domain extended: 1) in the x direction from $\sim 2\delta_0$ in front of the wedge leading edge to a distance $\sim 20\delta_0$ downstream; 2) in the y direction from $y=0$ to a distance $\sim 10\delta_0$ from the wedge surface; and 3) in the z direction from $z=0$ to a distance $\sim 6\delta_0$ above the tunnel floor. A total of 21 mesh points in the x direction, 36 points in the y direction (with 18 points in the viscous layer), and 28 points in the z direction (with 18 points in the viscous layer) were used for the present computations.

The turbulent model employed is an algebraic eddy-viscosity model modified in the corner region for the present three-dimensional configuration.[3] The boundary conditions, numerical method, and special numerical procedures used in the calculations presented herein are described in Refs. 3 and 4. Computation times to achieve fully converged solutions on a CDC 7600 were about 1.4 h for each case.

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

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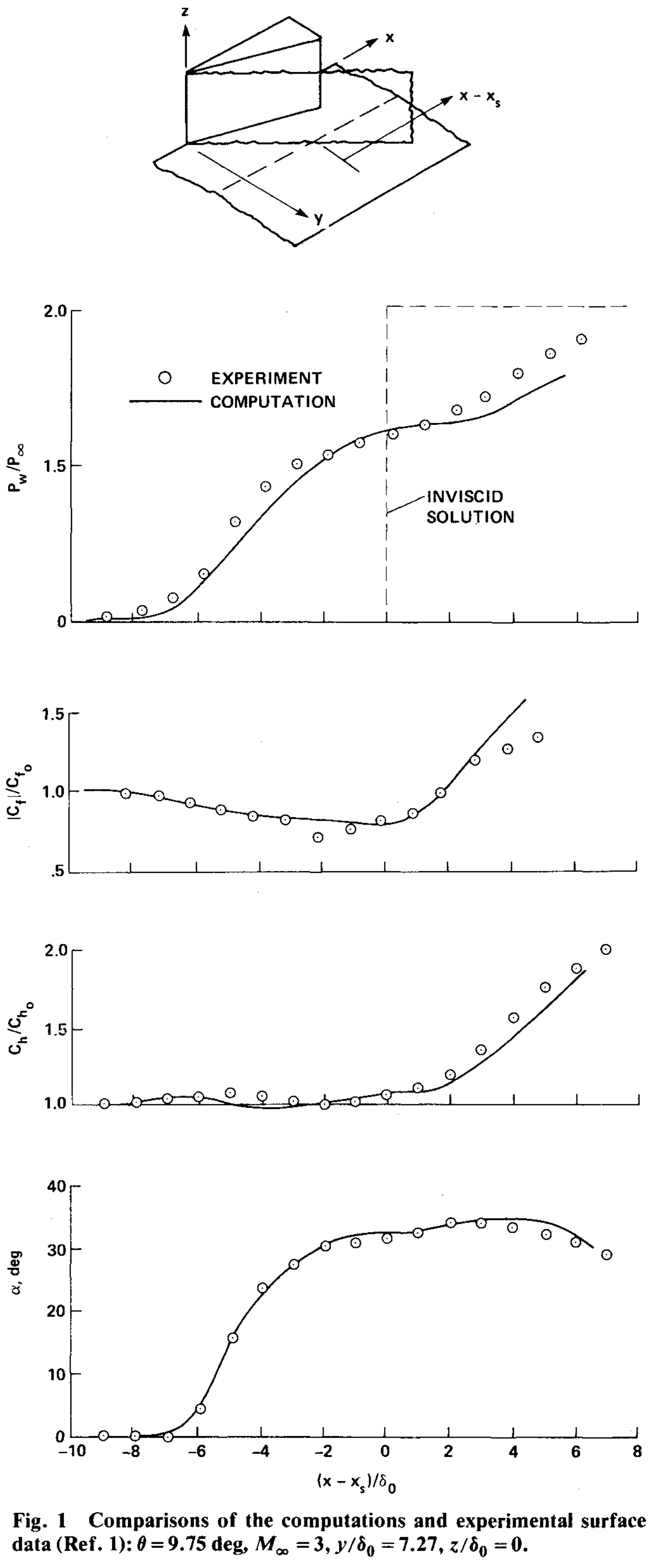

Fig. 1 Comparisons of the computations and experimental surface data (Ref. 1): $\theta = 9.75$ deg, $M_\infty = 3$, $y/\delta_0 = 7.27$, $z/\delta_0 = 0$.

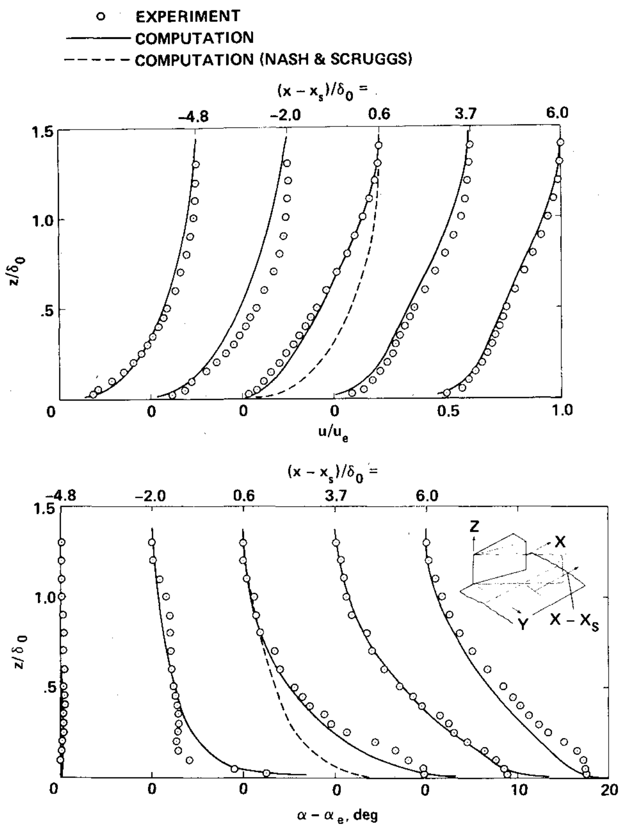

Fig. 2 Comparisons of the computations and experimental flowfield data (Ref. 2): $\theta = 8$ deg, $M_\infty = 2$, $y/\delta_0 = 5$.

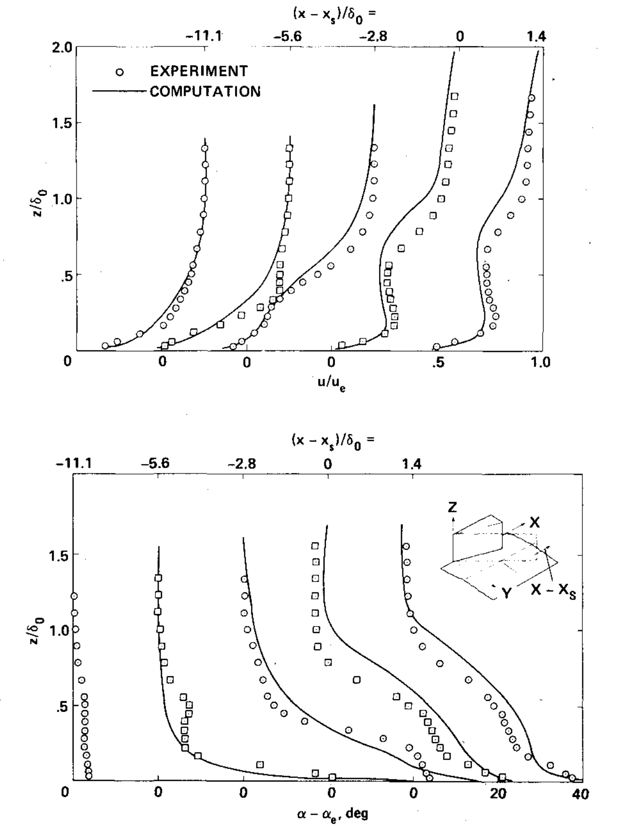

Fig. 3 Comparisons of the computations and experimental flowfield data (Ref. 2): $\theta = 16$ deg, $M_\infty = 4$, $y/\delta_0 = 5.56$.

Five experimental test flows have been calculated. These flows include two cases by Oskam et al.[1] and three cases by Peake.[2] The test conditions varied from Mach numbers of 2 to 4 and wedge angles θ from 3.75 to 16 deg. The computations are compared with the experimental surface measurements of Oskam et al.[1] in Fig. 1. For this case the surface pressure, skin-friction, and heat-transfer distributions are closely predicted. The computed surface streamline angles α are also in excellent agreement with the data.

Figure 2 shows detailed comparisons of the computations and measured streamwise velocity u and yaw-angle, $\alpha = \tan^{-1}(v/u)$, profiles at several x stations for the Peake $M_\infty = 2$, $\theta = 8$ deg flow. This is considered as a nonseparated flow case, and the present computed solutions are in very good agreement with the experimental data. The results of a three-dimensional boundary-layer code developed by Nash and Scruggs[5] are also shown in Fig. 2. This was the only case among the five considered in the present paper calculated in Ref. 5, and these boundary-layer computations do not predict the detailed flowfield correctly, even though they show reasonable agreement with the measured skin friction.[4] Figure 3 shows similar comparisons for the Peake $M_\infty = 4$, $\theta = 16$ deg test flow which is a substantial increase in shock-wave strength compared to the above flow, and is considered as a separated flow case. Except for a few minor deviations, the computed results are still in reasonably good agreement with the experimental data. It is interesting to note that the inflection in the velocity profiles at $(x - x_s)/\delta_0 = 0$ and 1.4 are closely reproduced.

Similar comparisons between the present computations and both the surface and flowfield data for the five test cases have been made in Ref. 4. In general the agreements are as good as the comparisons shown here. The results seem to show that the flowfield features are strongly dominated by the inviscid swept shock. Questions concerning the existence of a vortex and other physical aspects of this type of flowfield are also discussed in Ref. 4. The observations are not conclusive and further investigation is necessary.

The three-dimensional interaction of a swept shock wave with a turbulent boundary layer has been calculated successfully. Detailed comparisons with both surface and flowfield data from five experimental test flows have been made. The comparisons show very good agreement between the calculations and experiment.

References

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