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Transonic Turbulent Separated Flow Predictions Using a Two-Layer Turbulence Model

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Abstract

A NAVIER-STOKES code with algebraic stress model/k-ϵ two-layer turbulence model has been developed to compute the transonic turbulent flow over an axisymmetric secant-ogive-cylinder-boattail (SOCBT) projectile with a flat base and over an axisymmetric bump. The implicit upwind-biased algorithm with Harten's second-order upwind total variation diminishing discretization is extended to solve the higher order turbulent transport equations of the two-layer model for high accuracy and acceptable convergent rate. Computed results are compared with both the experimental data and the results using other turbulence models. It is found that improvement of the prediction and anisotropic turbulent natures, in the recirculating region downstream of the strong shock-wave/boundary-layer interaction flow, can be obtained using the two-layer model of turbulence.

Contents

In the past several years, considerable advances have been made in predictions of transonic turbulent separated flow. For the present study, the mixture of Rodi's[1] algebraic stress model (ASM) and Chien's[2] k-ϵ turbulence model is formed as the present ASM/k-ϵ two-layer model. The two models are matched at a preselected grid line and the number of node points in the inner layer corresponds to minimum $y^+_{\rm match} = 40$ in the boundary-layer type flow region. The extra equations of turbulent quantities of $(k, \epsilon, \overline{u'u'}, \overline{v'v'}, \overline{u'v'})$ or (k, ϵ) must be solved with the mass-averaged Navier-Stokes equations if an ASM or k-ϵ turbulent model is employed. The system of governing equations with these extra variables becomes not only larger but also stiffer and is difficult to solve. Harten's second-order upwind TVD scheme[3] is a good choice to discretize the convection terms and it is extended to solve the turbulent transport equations of the present two-layer model. In the present work, the mean flow equations and turbulent equations of k and ϵ can be decoupled, so that solving 4×4 (mean flowfield equations) and 2×2 (turbulent field equations) block tridiagonal matrices can be reduced to solving a 4×4 block tridiagonal matrix and two tridiagonal matrices (k and ϵ equations). These modifications improve the stability of the numerical computation and the details are given in Ref. 4. The nonlinear algebraic equations of ASM are solved simultaneously by Newton's method. About 15.4% more of the CPU time per iteration for the present ASM/k-ϵ two-layer model is required if it is compared with that of the k-ϵ turbulence model, which consumed a CPU time of 0.89 seconds per iteration on CRAY-XMP14. During the computation, the L2 residual can be reduced more than 4.5–5 orders lower after 7000–9000 iterations and the results can be considered as converged results. Numerical computations have been made for the following two transonic turbulent flow cases: 1) shock-induced separated flow over an axisymmetric bump for a freestream Mach number of 0.875 and a unit Reynolds number of 13.6×10^6/m and 2) flow over SOCBT projectile with a flat base at zero angle of attack for a freestream Mach number of 0.94 and a unit Reynolds number of 13×10^6/m.

The surface pressure distributions over a bump predicted by the ASM/k-ϵ two-layer model are compared in Fig. 1 with experimental data and with the computed results of other turbulence models. It is observed that the ASM/k-ϵ two-layer model and Johnson-King's[5] model produce the best pressure distributions in the recirculating region downstream of the strong shock-wave/boundary-layer interaction.

The comparison of the velocity profiles by the ASM/k-ϵ two-layer model and k-ϵ model (Fig. 2) shows that the ASM/k-ϵ two-layer model improves the prediction of mean velocity profiles in recirculating flowfield region downstream of the shock-wave/boundary-layer interaction ($X/C \le 1.125$), but the low Reynolds number k-ϵ turbulence model gives better velocity profiles in the region downstream of reattachment ($X/C \ge 1.25$). The ASM/k-ϵ model as well as the low Reynolds number k-ϵ turbulence model somewhat underestimates the separated extent near the wall. It seems that the near-wall turbulence model of the present ASM/k-ϵ study needs further improvements to get better simulation of separated flowfield. Good agreement with measurement at locations of reversal flow ($X/C \le 1.125$) is obtained by Johnson-King's model, but underpredictions of the velocity magnitude downstream of the reattachment ($X/C \ge 1.25$) is also shown. In general, the velocity profiles by Baldwin-Lomax's model[6] disagree with measurement in relatively large regions compared with the profiles by other turbulence models.

Figure 3 shows turbulent shear stress distribution at selected stations of a bump. In this figure, two sets of experimental results are presented. The circle symbols correspond to the Reynolds shear stress measured with the x-axis horizontal and y-axis vertical. The triangle symbols correspond to Reynolds shear stress obtained by performing a coordinate transformation of these data to account for the large anisotropies present in this flow. In this transformed coordinate system, the x axis is aligned with the direction of the flow at the location where

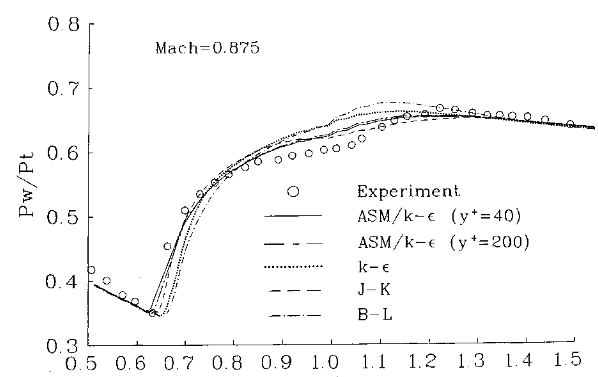

Fig. 1 Surface pressure distributions for different turbulence models ($M_\infty = 0.875$).

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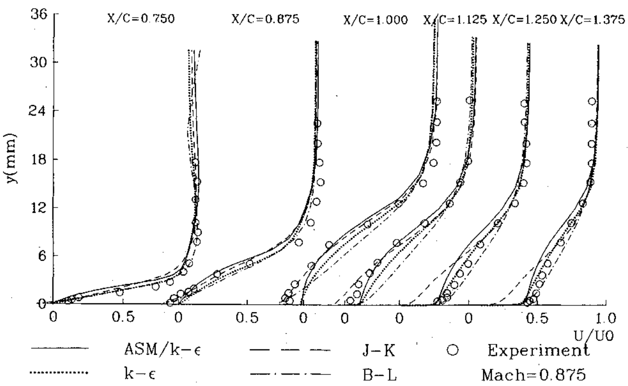

Fig. 2 Velocity profiles at various axial stations ($M_\infty = 0.875$).

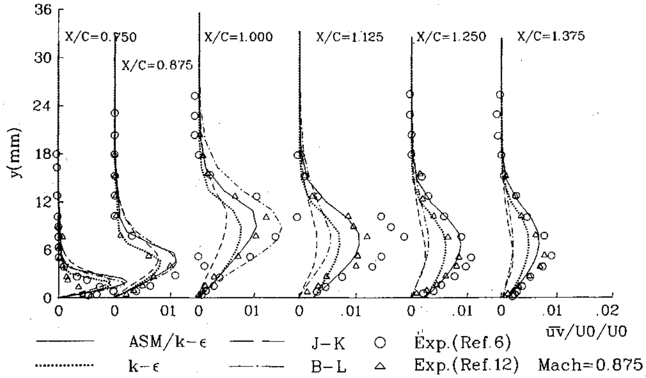

Fig. 3 Reynolds shear stress profiles at various axial stations ($M_\infty = 0.875$).

the Reynolds shear stress is a maximum.[5] Observation of this figure indicates that the ASM/k-ϵ model does obtain a significant improvement in predicting the Reynolds shear stress over all other turbulence models at all axial locations.

The computed surface pressure distribution over the SOCBT projectile with a flat base for Mach number of 0.94 is shown in Fig. 4 and is compared with the experimental data.[7,8] This figure shows the satisfactory predictions of surface pressure distributions on the boattail, where weak shock-wave/boundary-layer interaction and no separation are observed by using the ASM/k-ϵ two-layer model or low Reynolds number k-ϵ turbulence model. However, the surface pressure distributions on the projectile base predicted by both turbulence models are apparently different. The different results suggest that different turbulence models do have significant influence on the prediction of flowfield structures in the wake region. Further measurements on the base flow are needed to validate the proper use of turbulence models.

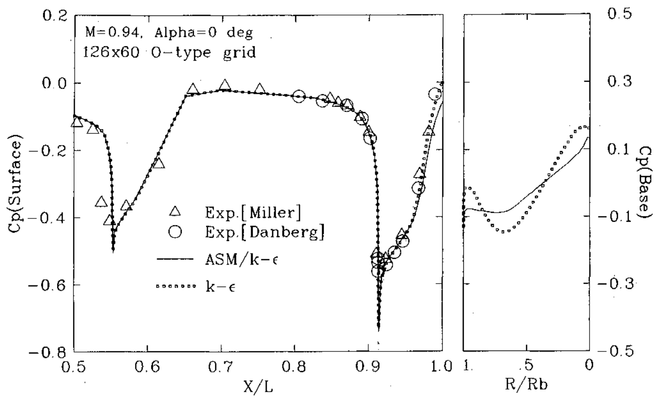

Fig. 4 Surface pressure coefficient distributions for different turbulence models ($M_\infty = 0.94$).

Acknowledgment

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