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Hypersonic Shock-Wave/Turbulent-Boundary-Layer Interaction Flows

C. C. Horstman*
NASA Ames Research Center, Moffett Field, California 94035

Abstract

THIS paper uses a two-dimensional/axisymmetric Navier-Stokes code to study the accuracy of the two-equation k-ϵ turbulence model[1] when compared with the hypersonic shock-wave/boundary-layer interaction data base.[2] Two modifications of the standard k-ϵ model are also investigated. The first is the new two-layer k-ϵ model developed by Rodi[3] that has had good success for separated flows at low speeds. The second is a modification developed to account for compressibility effects following the work of Rubesin[4] and Vuong and Coakley.[5] These three models are evaluated by comparison with the data. The relative merits of the modifications are discussed.

Contents

Seven two-dimensional and axisymmetric experimental investigations were chosen for the current turbulence model evaluation process. These investigations include all four hypersonic studies recommended by Settles and Dobson[2] plus a recommended supersonic compression corner case, an additional axisymmetric cylinder-flare study, and a recent impinging shock study described in the full paper. For all of the test cases, either the flare, corner, or incident shock angles were varied to obtain flowfields with and without separation. Solutions were obtained using the three turbulence models described previously for 21 test cases. Only a few representative results will be shown here. Details of the turbulence models and computations including a mesh resolution study are given in the full paper.

Comparison of the computations and experiment for three selected test cases are shown in Figs. 1–3. The test geometry for all three cases is an axisymmetric cylinder flare. An attached flow at Mach 7.1 is shown on Fig. 1, and two separated cases at Mach 7.1 and 9.2 are shown on Figs. 2 and 3, respectively. In all cases, the data and computations are normalized by the same number for each test flow, namely, the average experimental value ahead of the interaction. For each test case, solutions with the three turbulence models are shown. Rather than discussing the individual test cases, several general observations will be made that are valid for most or all of the comparisions (including the 18 additional test cases not shown here due to space limitations).

The results obtained using the standard k-ϵ model underpredict the separation size and overpredict the skin friction and heat transfer near reattachment for the separated flow cases by substantial amounts. It performs similarly in the adverse pressure gradient regions for attached flow cases. The compressible model is in all cases an improvement or at least equal in performance to the standard k-ϵ model. The compressibility modifications increase separation zone size and decrease skin friction and heat transfer at reattachment and in

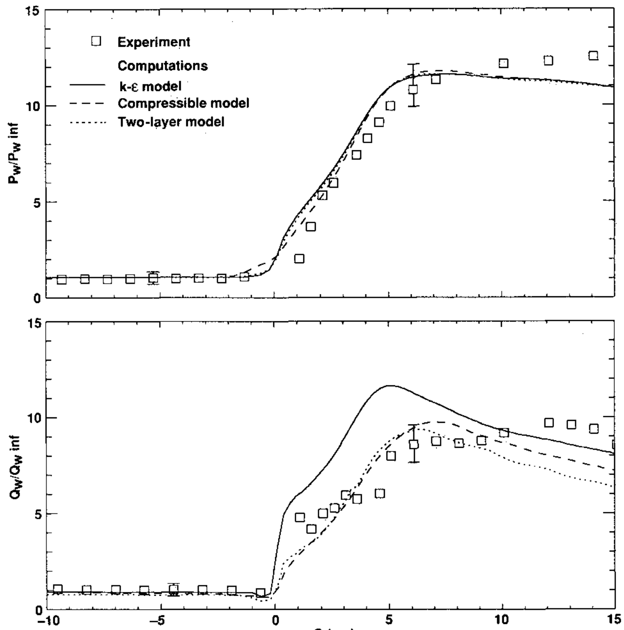

Fig. 1 Comparisons of surface pressure and heat transfer distributions; $M = 7.1$, 20-deg cylinder-flare flow.

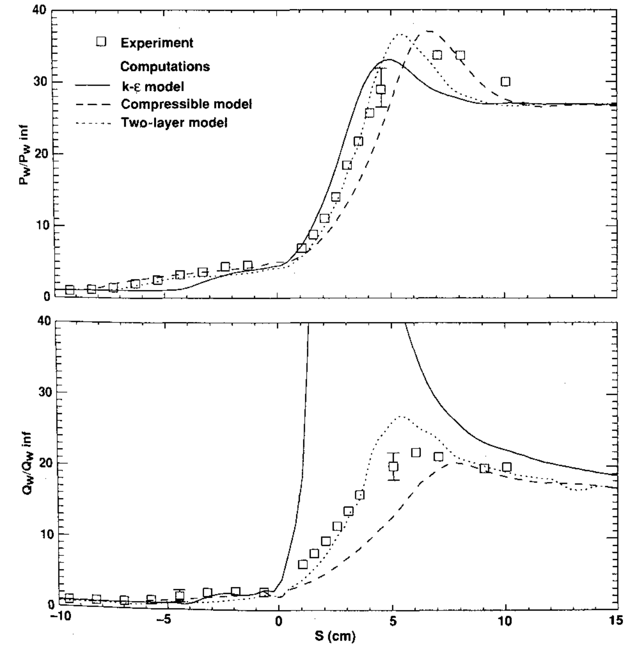

Fig. 2 Comparisons of surface pressure and heat transfer distributions; $M = 7.1$, 35-deg cylinder-flare flow.

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*Senior Scientist, Fluid Dynamics Division, Mail Stop 229-1. Associate Fellow AIAA.

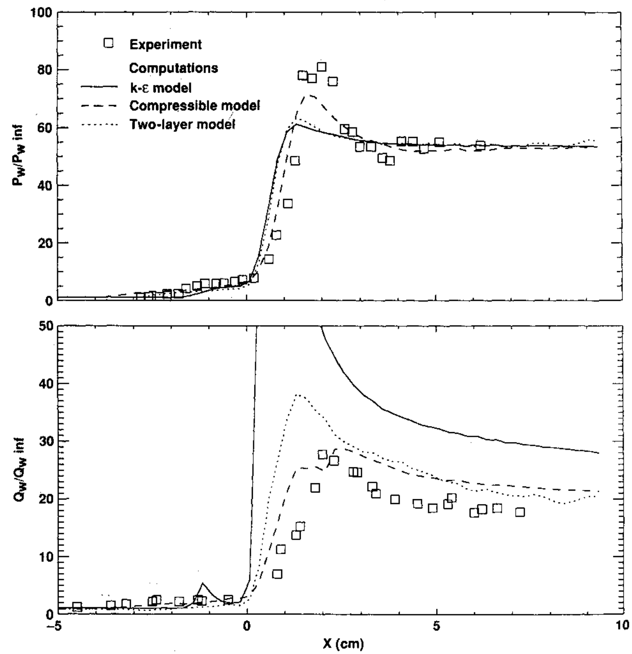

Fig. 3 Comparisons of surface pressure and heat transfer distributions; $M = 9.2$, 40-deg cylinder-flare flow.

adverse pressure gradient regions, thus giving better agreement with experiment.

The original intent of the two-layer model was to save computer time by allowing a more coarse mesh to be used.[3] In the present hypersonic flow computations, this did not prove to be the case. The mesh requirements for this model are almost identical to those for the standard model. The computed results using this model did increase the predicted separation zone size and lowered the skin friction and heat transfer at reattachment, similar to the compressible model. However, in regions of zero and low-pressure gradient the computed skin friction and heat transfer tended to underpredict the data. Other than this defect, the results are also better than or equal to the results using the standard model.

Solutions of the Reynolds-averaged Navier-Stokes equations using three turbulence models, including a model modified to account for compressibility effects, have been compared with several hypersonic shock-wave/turbulent-boundary-layer interaction test flows. The data available for comparison included surface pressure, skin friction, heat transfer, and the length of the flow separation zones. No single model accurately predicted all of the test cases; however, both the modified compressible model and the two-layer model showed substantial improvement over the standard k-ϵ model and could be used to predict unknown shock-wave/boundary-layer interaction flows with reasonable confidence. Considering the experimental errors present in the data (several experimenters do not even try to estimate their errors) and the ever-present computational errors due to numerical approximations and smoothing, the new compressible turbulence model described here seems adequate to solve these types of flowfields. Further improvements in turbulence modeling await a more complete data base that includes detailed fluctuating flow velocity, density, and temperature measurements.

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