NASA-CR-194547

TURBULENCE MODELING FOR HIGH SPEED COMPRESSIBLE FLOWS

FINAL REPORT

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Period Covered: May 16, 1991 - June 30, 1993
Grant Number: NAG-1-1287

(NASA-CR-194547) TURBULENCE MODELING FOR HIGH SPEED COMPRESSIBLE FLOWS Final Report, 16 May 1991 - 30 Jun. 1993 (North Carolina Agricultural and Technical State Univ.) 12 p

N94-20210

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G3/34 0189390

OBJECTIVES

The following grant objectives were delineated in the proposal to NASA:

(a) To offer course work in computational fluid dynamics (CFD) and related areas to enable mechanical engineering students at North Carolina A&T State University (N.C. A&TSU) to pursue M.S. studies in CFD. Hopefully, some of the students will subsequently work on Ph.D. degrees in CFD.

(b) To enable students and faculty at N.C. A&TSU to engage in research in high speed compressible flows.

RESULTS

Since no CFD - related activity existed at N.C. A&TSU before the start of the NASA grant period, training of students in the CFD area and initiation of research in high speed compressible flows were proposed as the key aspects of the project. To that end, the following results were achieved:

(a) Graduate-level courses in CFD, boundary layer theory, and fluid dynamics were offered. This effort included initiating a CFD course for graduate students.

(b) Ms. Cheryl Sellers, a minority female, worked on her M.S. thesis under the supervision of the principal investigator, Dr. Suresh Chandra. The research work focussed on studying compressibility effects in high speed flows. Specifically, a modified compressible dissipation model, which included a fourth order turbulent Mach number term, was incorporated into the SPARK code and verified for the air-air mixing layer case. The results obtained for this case were compared with a wide variety of experimental data to discern the trends in the mixing layer growth rates with varying convective Mach numbers. Comparison of the predictions of the study with the results of several analytical models was also carried out. Both agreements and discrepancies were analyzed. The details of the research study are described in the publication entitled "Compressibility Effects in Modeling Turbulent High Speed Mixing Layers", which is attached to this report.

Ms. Sellers received her M.S. degree from N.C. A&TSU in Fall 1992 and is currently working on her Ph.D. degree in CFD at the University of Illinois.

PUBLICATIONS/PRESENTATIONS

The following publications and conference presentations have resulted from the research conducted under the NASA grant:

1. "Study of Compressibility Effects in Turbulent Shear Flows", ASME Fluids Engineering Conference, Los Angeles, CA, June 1992.

2. "Compressibility Effects in Modeling Turbulent High Speed Mixing Layers," Submitted for publication in International Journal of Modern Physics and Computers.

3. "Compressibility Effects in Modeling Turbulent High Speed Mixing Layers", ASME Fluids Engineering Conference, Washington, DC, June 1993.

COMPRESSIBILITY EFFECTS IN MODELING TURBULENT HIGH SPEED MIXING LAYERS

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ABSTRACT

For high speed shear layers, variable density extensions of standard incompressible turbulence models have not proven to be adequate in explaining the experimentally observed reduction in growth rate with increase in the convective Mach number. Turbulence modeling for compressible flows has to account for additional correlations involving both thermodynamic quantities and the fluctuating dilatation. Recently, Sarkar et al. suggested that, in addition to modeling the pressure dilatation, another dilatational correlation - the compressible dissipation - should be considered because of the enhanced dissipation known to be present in compressible turbulence. Specifically, this compressible dissipation correction is proportional to the second and fourth powers of the turbulent Mach number which is defined in terms of the turbulent kinetic energy and the local speed of sound. Narayan and Sekar have used the compressibility-corrected model - limited to the second power of the turbulent Mach number - with the SPARK code for the computation of high speed shear layers and have obtained satisfactory agreement with some of the available experimental data.

The simple algebraic compressibility model by Sarkar et al. has been modified to include a fourth order turbulent Mach number term. Comparison of the predictions with results of several analytical models and experimental work has been carried out; both agreement and discrepancies are analyzed.

INTRODUCTION

In recent years, considerable interest has been shown in the United States and other developed nations in the development of airbreathing hypersonic vehicles. The task of arriving at an acceptable propulsion system is a complex one. In one approach, a highly integrated, hydrogen-fueled supersonic combustion ramjet (scramjet) engine is considered to be a viable propulsion system. Research is being carried out at numerous research centers so that an understanding of the complex flow field inside the scramjet engine can be obtained. The flow field is governed by the Navier-Stokes equations coupled with a system of equations describing the chemical reactions that take place. The flow is expected to be turbulent in most part of the combustor, thus necessitating an analysis which is capable of addressing compressible turbulent reacting flows. The interaction between turbulence and chemical reactions is an important issue in this analysis. It is widely acknowledged that the exact solution of complex flows such as the ones in the scramjet engine is impossible because of the wide range of length and time scales of turbulence. Turbulence modeling, therefore, affords the necessary simplified treatment of the turbulent flows. Acceptable turbulence models for the flows in the scramjet engine will have to take into account the effects of turbulence on the flow as a whole and on the chemical reactions in particular.

Various turbulence models for different flow configurations have been used in recent years. These models range from the simplest mixing length or zero-equation models to the most general Reynolds stress closures. Work is also being done on developing other means of analyzing turbulent flows such as large eddy simulation. Several useful reviews of the turbulence modeling work exist in literature [1,2,3].

One class of models that is widely used is the two-equation model in which a differential equation for the mean turbulent kinetic energy and another for some form of the length scale of turbulence are solved along with the averaged forms of the Navier-Stokes equations. Good results have been obtained for many flow situations by using the two-equation models. They are relatively easy to implement in a given solution procedure and provide computational economy as compared with the Reynolds stress models. In the past, much of the turbulence modeling work has been restricted to incompressible flows with somewhat arbitrary modifications applied to account for compressibility. Various problems have been encountered in developing a fully compressible turbulence model because the modeling of the averaged equations for compressible flows is not feasible using the known techniques. Narayan and Sekar [4] used a two-equation turbulence model with a compressibility correction derived from the Reynolds stress closure model of Sarkar et al. [5]. The two turbulence variables in their work are the turbulent kinetic energy (TKE) and its dissipation rate. They tested the model on a spatially developing, supersonic, chemically reacting plane mixing layer. A major portion of the chemical reactions in the scramjet combustor occur in mixing layers and all the complexities introduced by fluid mechanics, combustion chemistry, and the interaction between them are retained by the reacting mixing layer. Reference [6] chronicles recent developments in the area of turbulent shear flows. Narayan and Sekar used the compressibility correction model - limited to the second power of the turbulent Mach number - with the SPARK code (developed at the NASA Langley Research Center) for the computation of high speed shear layers and obtained good results with some of the available experimental data.

In the present work, a modified compressible dissipation correction model of Sarkar et al. [5], which includes a fourth order turbulent Mach number term, is incorporated into the SPARK code and is verified for the computation of the air-air mixing layer case. Results obtained for this case are compared with available experimental data to discern the trends in the mixing layer growth rates with varying convective Mach numbers. Comparison of the predictions with results of several analytical models is also carried out, and both agreement and discrepancies are analyzed.

Modeled Equations

The closure of the turbulent flow governing equations incorporates the use of the Boussinesq approximation which relates Reynolds stresses to the mean strain rate through the following equation:

$$-\overline{\rho u_i'' u_j''} = \bar{\mu}_t \left(\frac{\partial \tilde{U}_i}{\partial x_j} + \frac{\partial \tilde{U}_j}{\partial x_i} \right) - \frac{2}{3} \bar{\rho}\, k\, \delta_{ij}$$

where $\bar{\mu}_t$ is the turbulent or eddy viscosity expressed in terms of some characteristic length scale $(k^{\frac{3}{2}}/\epsilon)$ and a velocity scale $(k^{\frac{1}{2}})$,yielding the following expression for $\bar{\mu}_t$;

$$\bar{\mu}_t = C_\mu \rho \frac{k^2}{\epsilon}$$

Details of the modeling of the mean continuity, momentum, and energy equation are provided in [4]. In modeling the TKE (k) equation and the dissipation rate (ϵ) equation, Narayan and Sekar [4] relied on Sarkar's model [5] for compressible dissipation expressed in terms of ϵ and the local turbulent Mach number (M_t) . This model is given by $\epsilon_c = \alpha M_t^2 \epsilon$, where $M_t^2 = 2k/a^2$, a = local speed of sound, and the model constant α = 1.0. The modeled k-equation is

$$\frac{\partial \bar{\rho} k}{\partial t} + \frac{\partial \bar{\rho} k \tilde{U}_j}{\partial x_j} = P_k - \bar{\rho}\epsilon (1 + \alpha M_t^2) + \frac{\partial}{\partial x_j} [(\bar{\mu} + \frac{\bar{\mu}_t}{6k}) \frac{\partial k}{\partial x j}]$$

where P_k = Production term in the k - equation

$$P_k = -\rho \overline{u_i'' u_j''} \frac{\partial \tilde{U}_i}{\partial x_j}$$

Because of the extreme difficulties encountered in attempting to model the exact equation for the dissipation rate ϵ , the incompressible form of the ϵ -equation is used in [4]. The modeled form of this equation is

$$\frac{\partial \bar{\rho} \epsilon}{\partial t} + \frac{\partial \bar{\rho} \epsilon \tilde{U} j}{\partial x_j} = (C_1 P_k - C_2 \bar{\rho} \epsilon) \frac{\epsilon}{k} + \frac{\partial}{\partial x_j} [(\bar{\mu} + \frac{\bar{\mu}_t}{6_\epsilon}) \frac{\partial \epsilon}{\partial x_j}]$$

Once the governing equations and the required modeling are available, the equations are discretized and integrated in space and time toward steady state solutions.

In the present study, the model of Sarkar et al. [5], which is based on an asymptotic analysis of the compressible Navier-Stokes equations, has been modified. The modified model for ϵ_c includes a fourth order M_t term, which Sarkar et al. consider to be a natural extension of their simplified model when flows of large Mach numbers are considered. The modified model is given by

$$\epsilon_c = (\alpha_1 M_t^2 + \alpha_2 M_t^4)\epsilon$$

where the model constants are, in general, less than 1.0.

Results and Analysis

A two-dimensional, high speed mixing layer is considered in this study. A schematic of this flow problem is given Figure 1. A wide variety of experimental data has been collected from a review of literature, and the calculated mixing layer growth rates based on the modified compressible dissipation model are compared with the available experimental data. Additionally, the predicted growth rates are compared with several compressibility models using other turbulence modeling techniques. The mixing layer thickness δ is defined as

$$\delta = \frac{U_a - U_b}{\left(\frac{\partial u}{\partial y}\right)_{max}}$$

where a and b are the high speed and low speed streams, respectively. Growth rate comparisons with experimental and analytical data are presented in terms of a parameter C_δ which is defined as $C_\delta = \frac{d\delta}{dx}\frac{U_a+U_b}{U_a-U_b}$ and C_{δ_o} is its value for incompressible flow (assumed to be at a convective Mach number of 0.1). The convective Mach number is defined as

$$M_c = \frac{U_a - U_b}{a_a + a_b}$$

Figure 2 provides comparison of the modified compressibility model results for various values of α_1 and α_2 with a variety of experimental data [7,8,9,10,11,12,13,14]. It is noted that α_1=1.0 and α_2=0 corresponds to predictions of Nanayan and Sekar [4]. It is clear that α_1=0.5 and α_2=0.5 provides the best agreement with the experimental data from numerous sources. The modified model with these values of the model constants also provides a significantly improved agreement with experiments than the one obtained in [4]. The fact that the α_1 and α_2 values of less than 1.0 provide more acceptable predictions of the mixing layer growth rates is supported by noting that Sarkar et al. [5] assumed $M_t<0.5$ for their analysis and that for the conditions of the present study, M_t is almost always greater than 0.7. Also, several researchers in recent years have used $\alpha_1<1.0$ values for high speed flows. Figure 3 isolates the comparison of the results of the modified model (α_1=0.5, α_2=0.5) with available experimental data. Figure 4 gives the additional comparison of the modified model results with the (a) Reynolds stress model (RSM) of Balakrishnan and Abdol-Hamid [15], (b) no compressibility correction case (α_1=0, α_2=0), and (c) simplified compressibility model (α_1=1.0, α_2=0). The modified model is shown to provide improved predictions than other models. Figures 5 and 6 show comparisons of the results based on the modified compressibility model with those of models using other turbulence modeling techniques. The experimental data are also shown on these plots for comparison with various analytical models. It appears that the modified one-equation algebraic model of Burr and Dutton [16,17] and the model by Viswanathan and Morris [18] show a better correlation with the experimental data for $M_c<0.75$, while the modified model proposed in this study gives better results for $M_c>0.75$. The compressibility model in [16,17] accounts for variations in the anisotropy of the normal stresses through modifications of the pressure strain terms of the Reynolds stress transport equations. The model in [18] considers large scale structures as linear instability waves and shows that the development of free shear layers is closely related to the stability characteristics of the mean flow. It is, therefore, likely that for $M_c<0.75$, the flow instabilities are significant in modeling compressibility effects while the compressibility dissipation and pressure dilation are relatively more important for $M_c>0.75$.

ACKNOWLEDGEMENTS

This work was supported by NASA Langely Research Center (Grant NAG-1-1287) and by the NASA Aerospace Research Center at North Carolina A & T State University (Grant NAGW-2924). The authors would like to acknowledge Dr. Thomas B. Gatski and Dr. J. R. Narayan of the Theoretical Flow Physics Branch at Langley for their valuable assistance and guidance.

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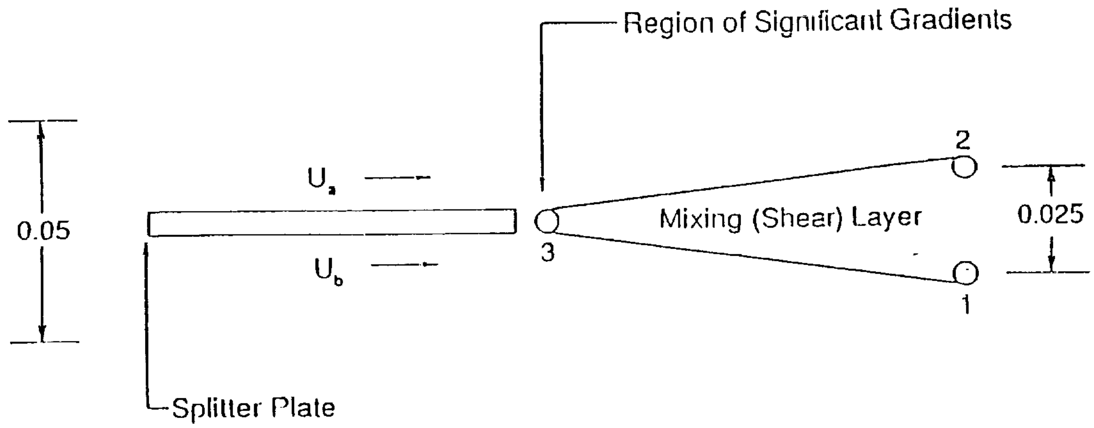

FIGURE 1. SCHEMATIC OF MIXING LAYER

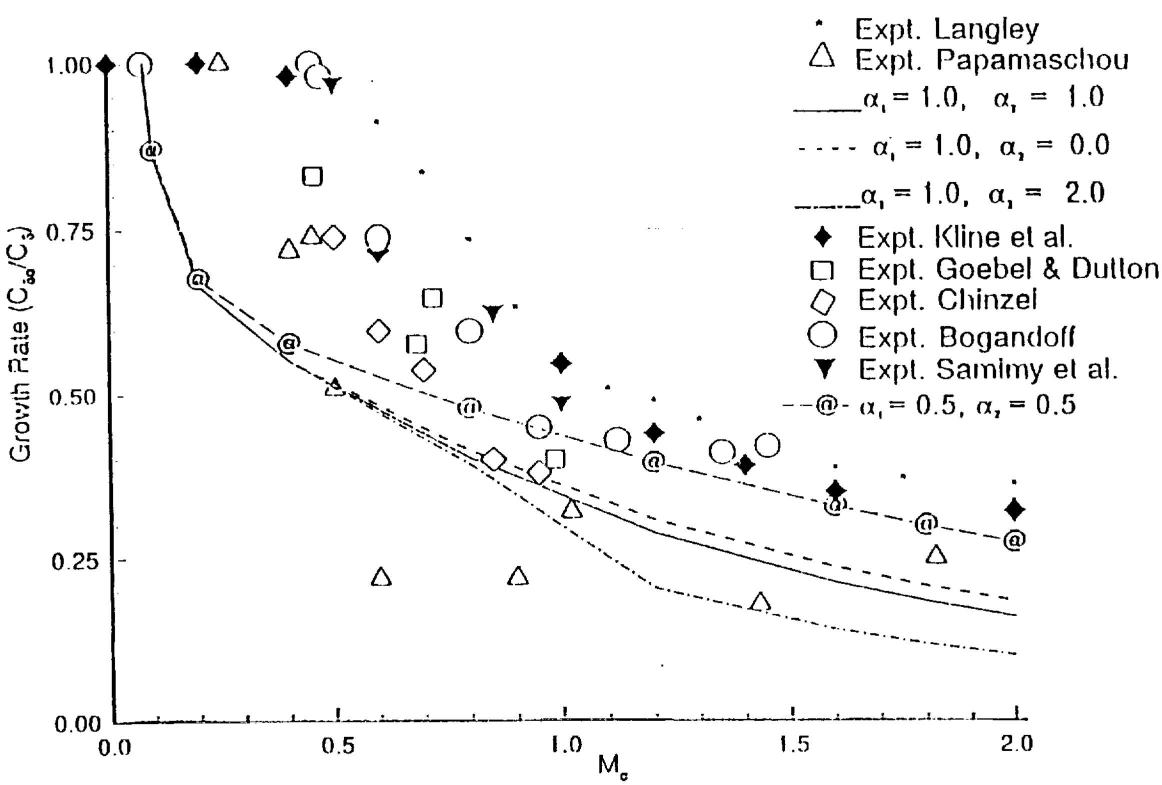

FIGURE 2 COMPARISON OF MODIFIED k-ε MODEL RESULTS WITH EXPERIMENTAL DATA

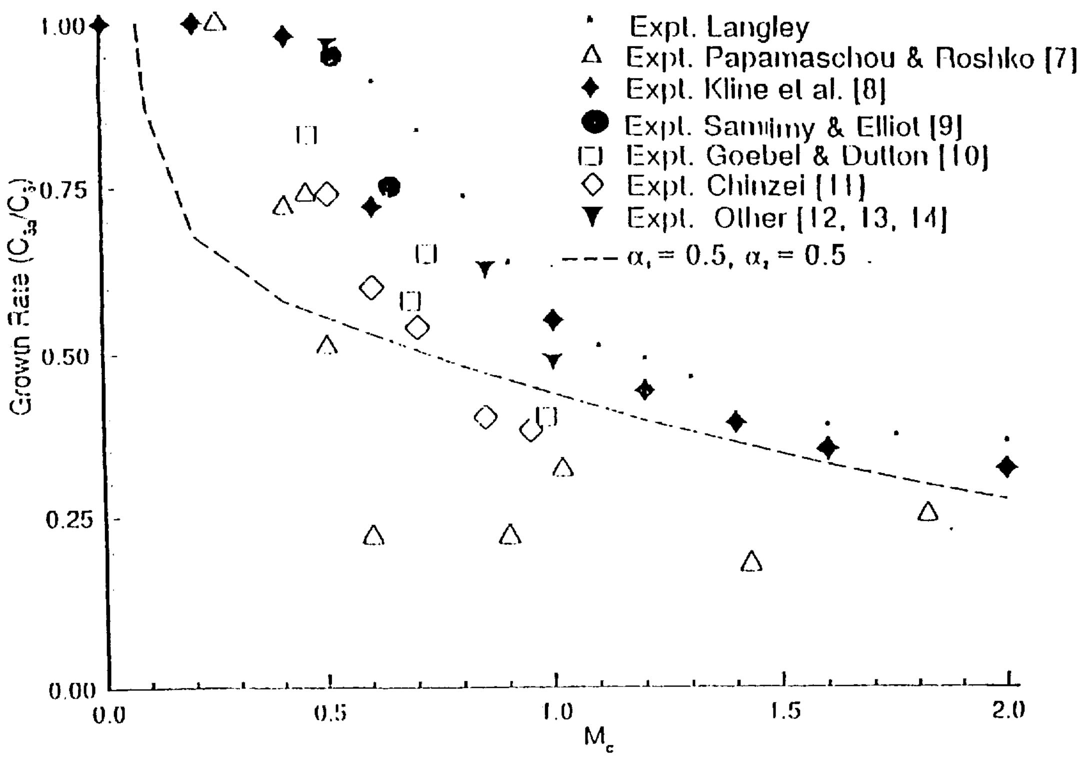

FIGURE 3 COMPARISON OF MODIFIED k-ε MODEL RESULTS WITH EXPERIMENTAL DATA

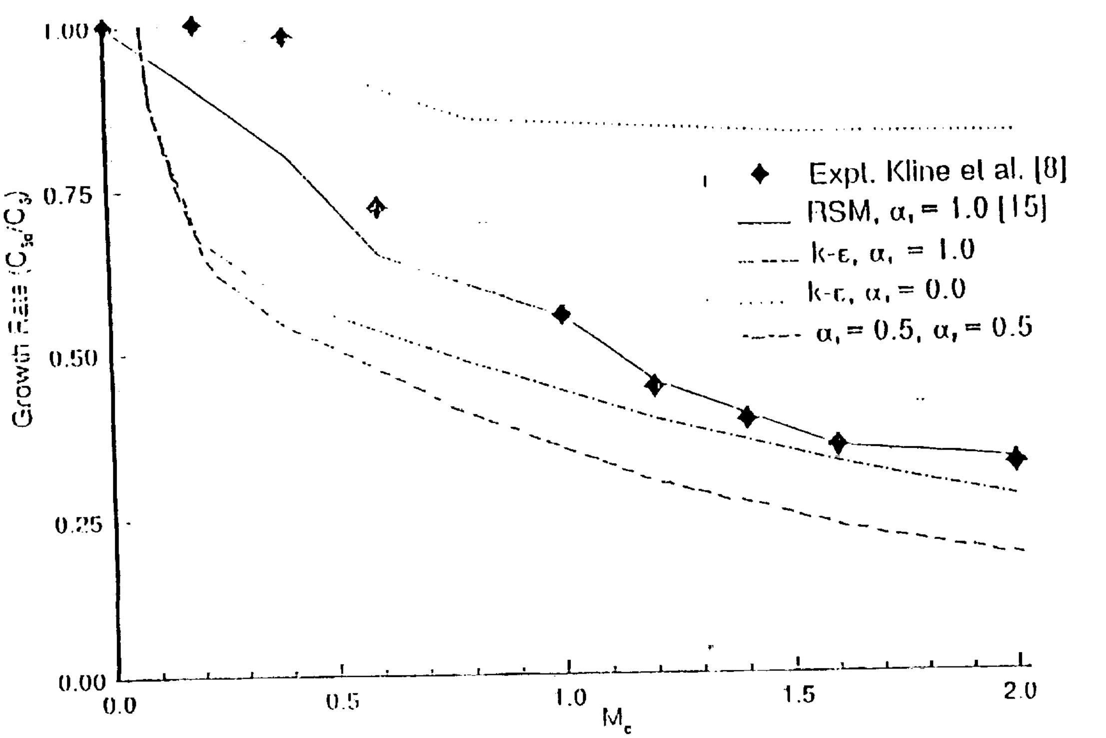

FIGURE 4 COMPARISON OF RSM WITH MODIFIED k-ε MODEL

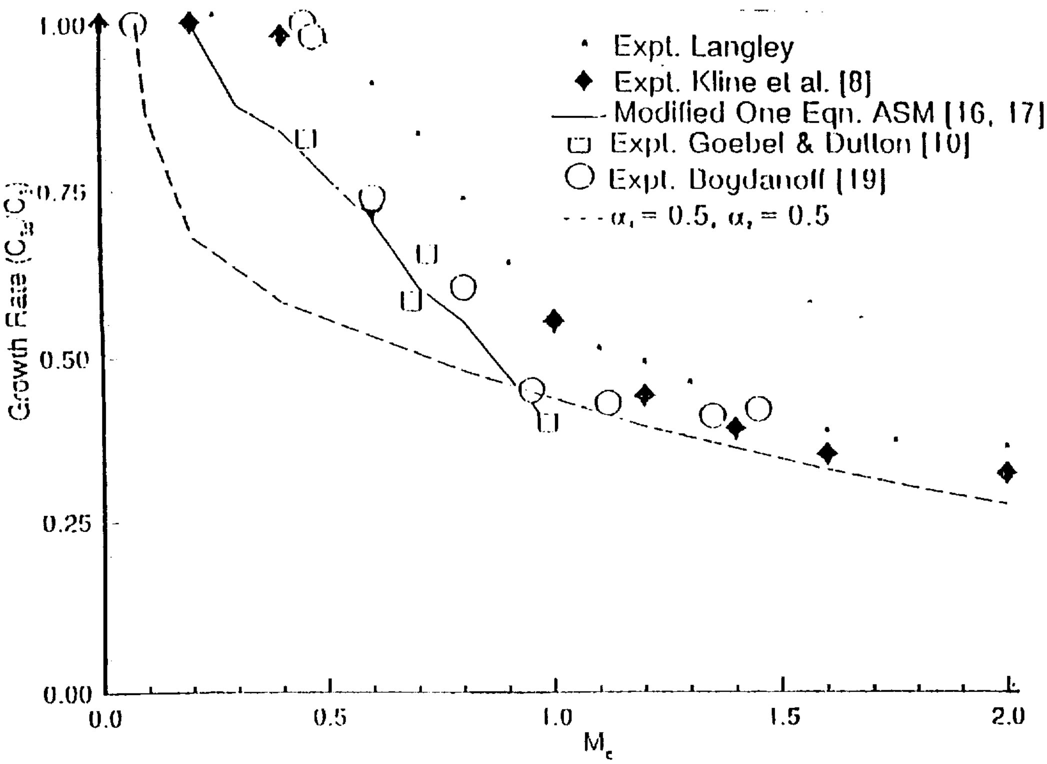

FIGURE 5 COMPARISON OF ONE-EQN ASM WITH MODIFIED k-ε MODEL

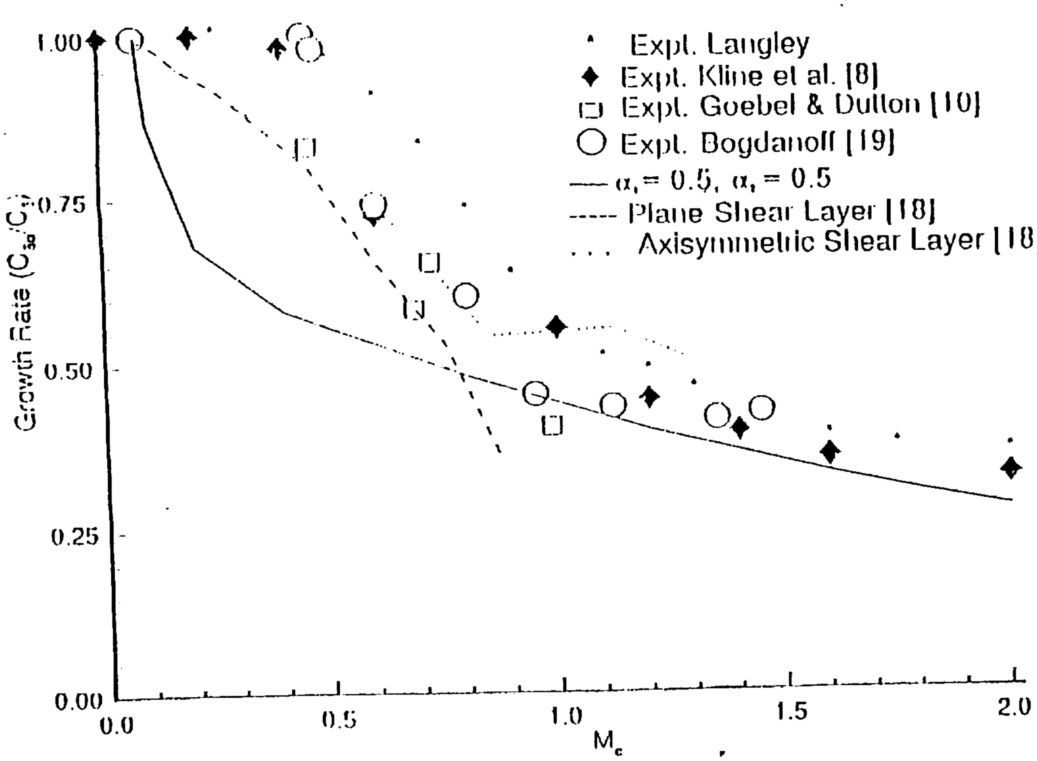

FIGURE 6 COMPARISON OF OTHER MODELS WITH MODIFIED k-ε MODEL