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THE APPLICABILITY OF TURBULENCE MODELS TO AERODYNAMIC AND PROPULSION FLOWFIELDS AT McDONNELL DOUGLAS AEROSPACE

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Objective

- Evaluate turbulence models for integrated aircraft components such as the forebody, wing, inlet, diffuser, nozzle, and afterbody

Approach

- Integrate turbulence models into existing Navier–Stokes program maintaining zonal philosophy
- Introduce corrections to baseline turbulence models to account for additional affects such as compressibility or separation
- Develop algorithmic improvements for better numerical stability and robustness
- Compare the strengths and weaknesses of turbulence models
- Determine applicability of algebraic, one–equation, and two–equation turbulence models for typical complex flows and geometries

Turbulence Modeling Capabilities

- *Algebraic Models*
  - Cebeci–Smith boundary layer model
  - Baldwin–Lomax boundary layer model
  - P. D. Thomas shear layer model

- *One–Equation Models*
  - Baldwin–Barth
  - Spalart–Allmaras

- *Two–Equation Models*
  - High Reynolds number $k - \epsilon$
  - Low Reynolds number $k - \epsilon$ (Jones–Launder, Speziale, Chien, Lam–Bremhorst, So, and Huang–Coakley)
  - Wilcox $k - \omega$
  - Menter baseline and shear–stress transport blended $k - \omega/k - \epsilon$

Navier–Stokes Time–Dependent Algorithm NASTD

- *Euler/Navier–Stokes Equations*
  - Laminar or Turbulent
  - Ideal Gas, Thermally Perfect Air, Equilibrium or Nonequilibrium Chemistry
- *Finite Volume Formulation*
  - Roe and Coakley Flux Difference Split Schemes, Optional TVD Schemes
- *Solution Update Procedure*
  - Approximate Factorization
  - Runge–Kutta Time Stepping
  - Iterative Space Marching (PNS)
- *Geometric Capabilities/Generalizations*
  - Zonal Capabilities and Flexible Boundary Conditions
  - Grid Sequencing
  - Overlapping Grids
- *Turbulence Models*
  - Cebeci–Smith, Baldwin–Lomax and P. D. Thomas Algebraic Models
  - Baldwin–Barth and Spalart–Allmaras One–Equation Models
  - Six Low Reynolds Number $k - \epsilon$ Models
  - $k - \omega$ and Menter blended $k - \omega/k - \epsilon$ Models

Selected Applications

- Transonic Supercritical Airfoil
- Three-Element High-Lift System
- Single Slot 2–D Ejector Nozzle
- Confluent Mixer
- Highly Offset 3–D Diffuser

Modifications to Production Term

Default calculation of production:

$$P_k = \frac{\bar{\mu}_t}{Re}\left[\frac{1}{2}\left(\frac{\partial \tilde{u}_i}{\partial x_j} + \frac{\partial \tilde{u}_j}{\partial x_i}\right)^2 - \frac{2}{3}\left(\frac{\partial \tilde{u}_k}{\partial x_k}\right)^2\right] - \frac{2}{3}\bar{\rho}\, k\, \frac{\partial \tilde{u}_k}{\partial x_k}$$

Vorticity used in production:

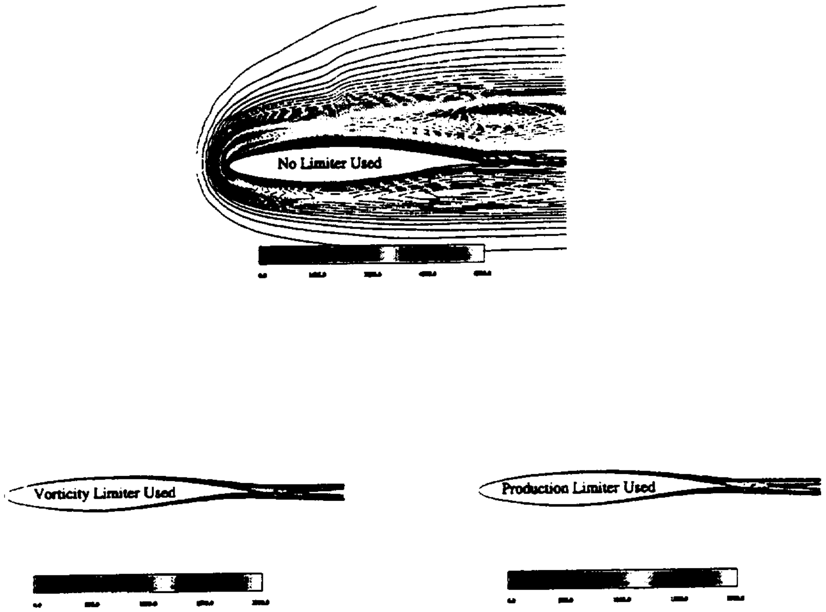
$$P_k^* = \frac{\bar{\mu}_t}{Re}|\omega|^2$$

Production limiter used:

$$P_k^* = \min(P_k, 20D_k) = \min(P_k, 20\, c_2\, \rho\, k\, Re)$$

Effect of Production Limiter for the Chien k–ε Model

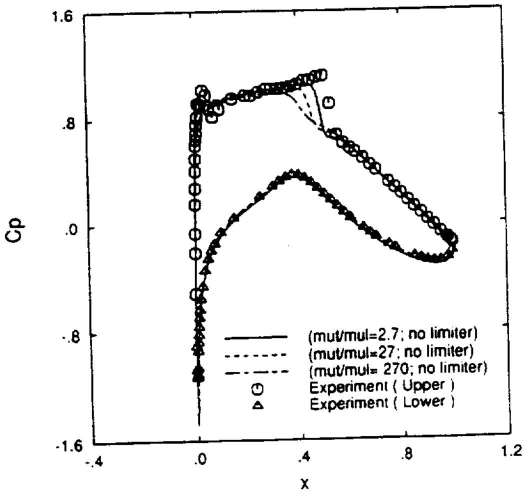
RAE Airfoil Analysis, Turbulent Viscosity Contours
Mach = 0.725, α = 2.55 deg., Re = 6.5 Million



RAE Airfoil Analysis

$M_\infty = 0.725$, $\alpha = 2.55°$, $Re = 6.5$ Million

Effect of Freestream Turbulence Level on Surface Pressure
Chien $k - \epsilon$ Turbulence Model



RAE Airfoil Analysis
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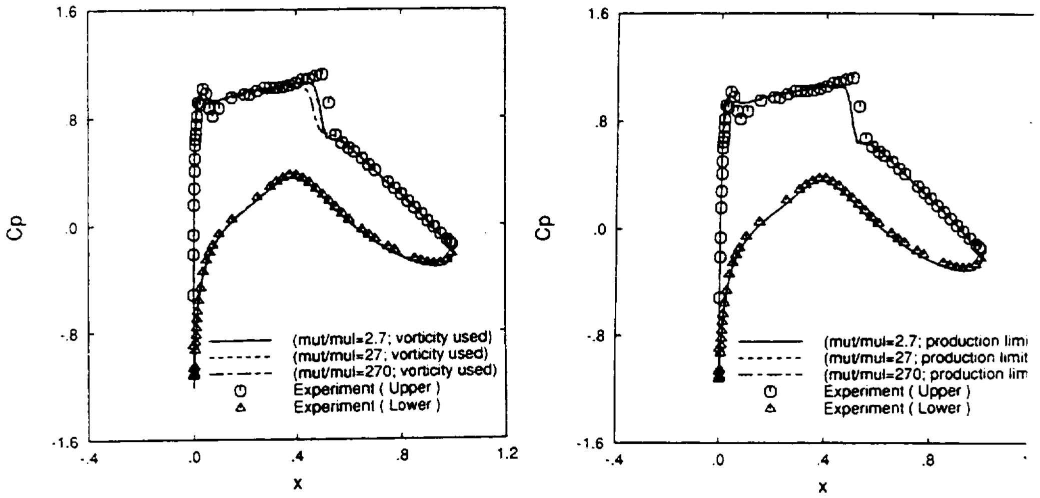
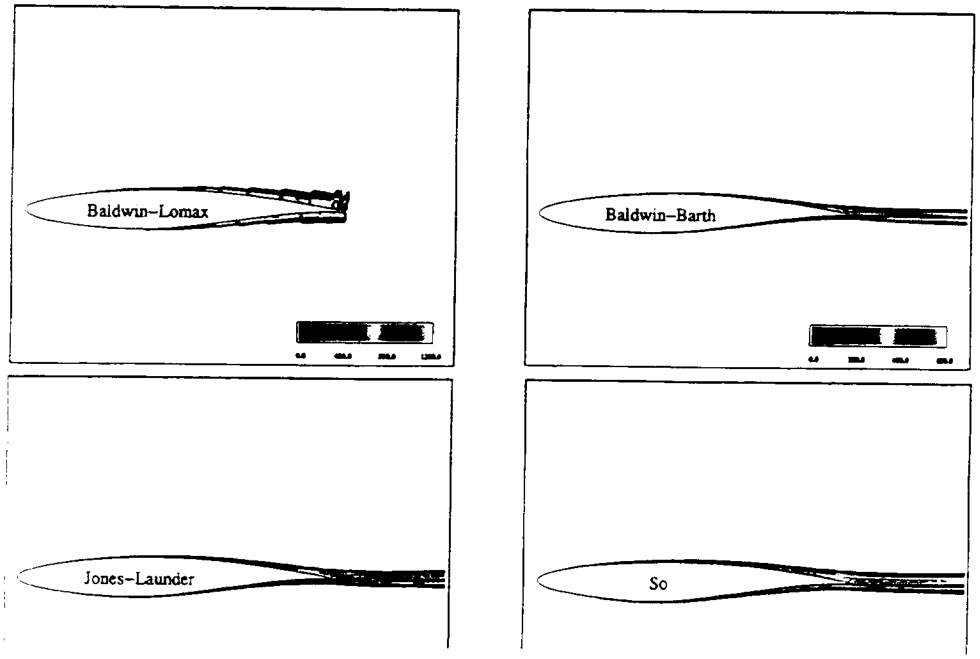
Production Limiter Used

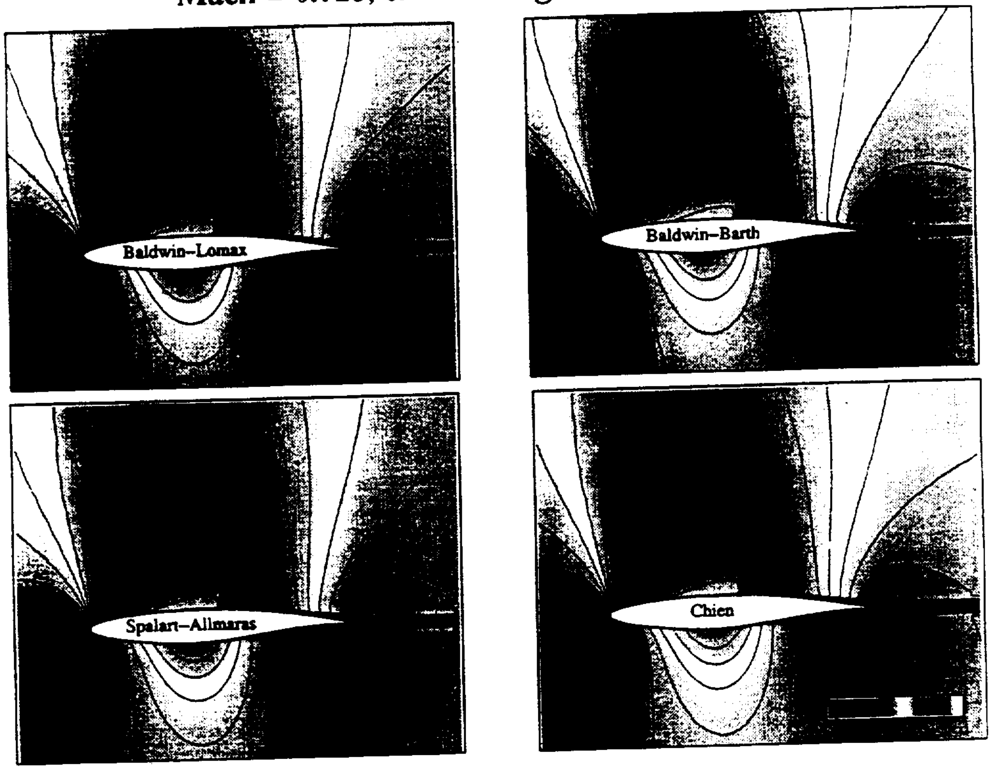
Chien $k - \epsilon$ Turbulence Model



RAE Airfoil Analysis, Turbulent Viscosity Contours
Mach = 0.725, α =2.55 deg., Re = 6.5 Million



RAE Airfoil Analysis, Mach Contours
Mach = 0.725, α =2.55 deg., Re = 6.5 Million



RAE Airfoil Analysis
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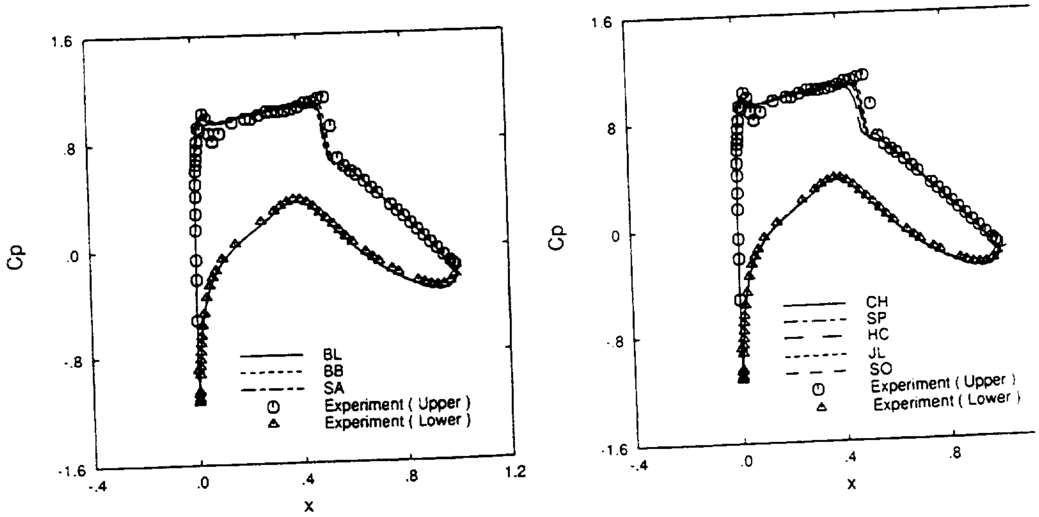
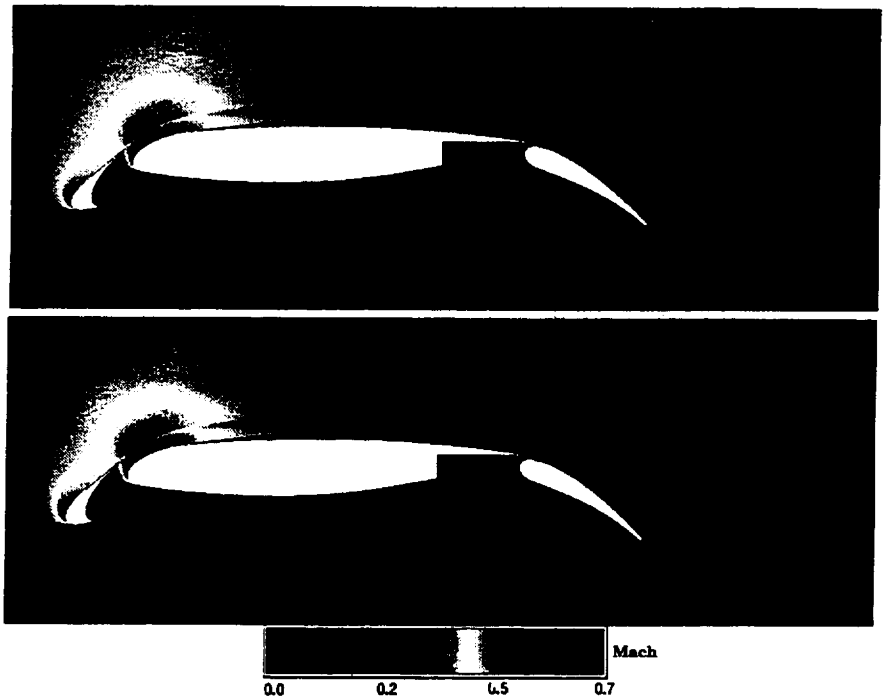
Effect of Turbulence Model on Surface Pressure



NASTD Solutionof MDA Three-Element High-Lift System

M = 0.2, AOA = 16.21



RAE Airfoil Analysis

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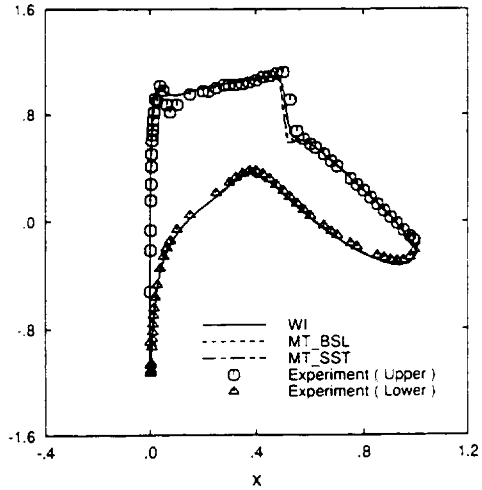
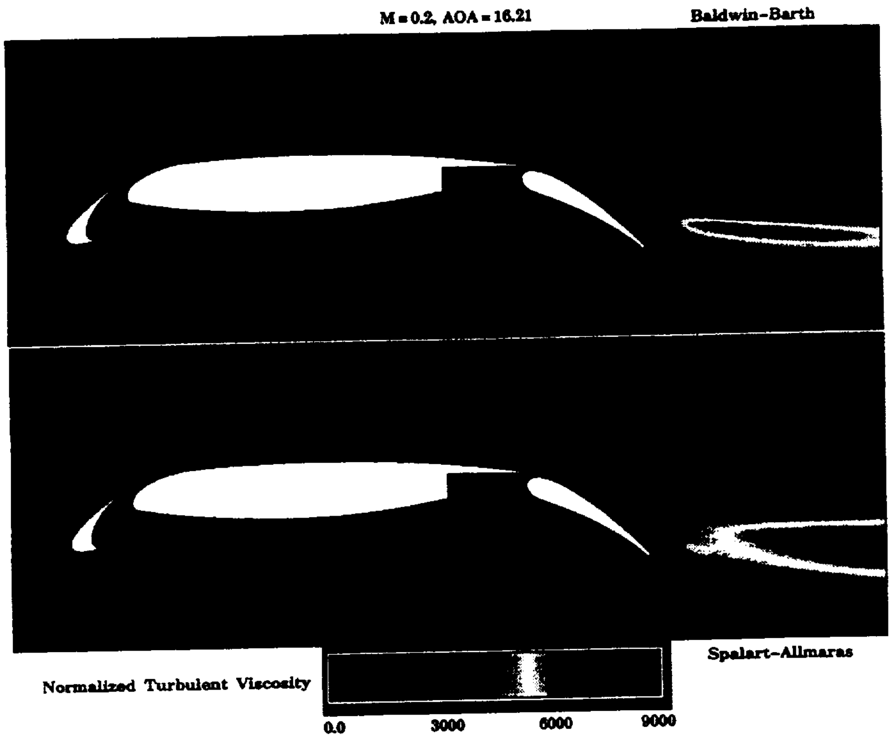
Effect of Turbulence Model on Surface Pressure

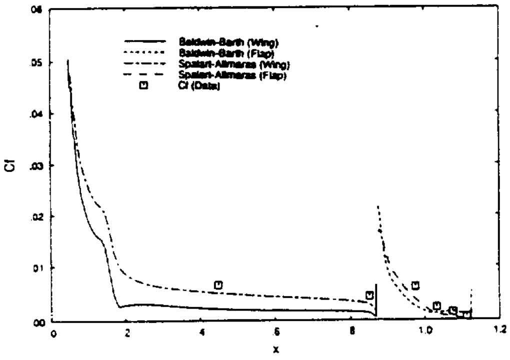


NASTD Solution of MDA Three-Element High-Lift System

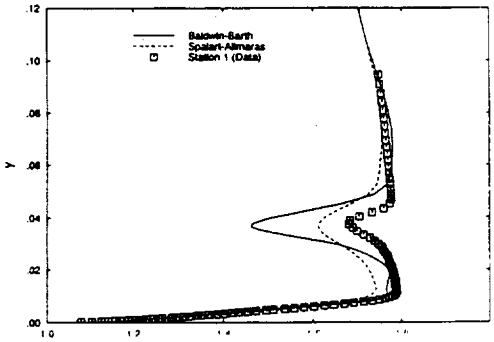


More Accurate Solutions Have Been Obtained With One-Equation Spalart-Allmaras Turbulence Model

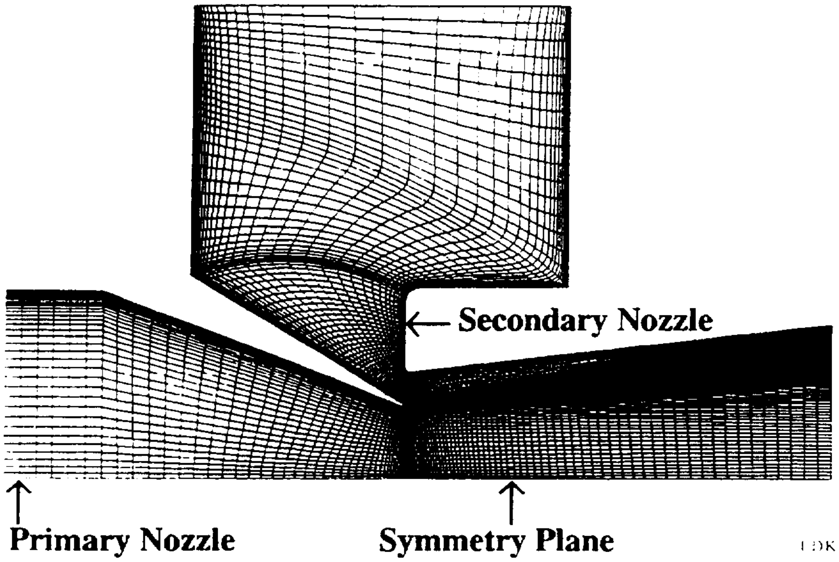
Skin Friction Coefficients on the upper Surfaces



Velocity Profile at Station 1 on the Wing (M=0.2, α=16.21)



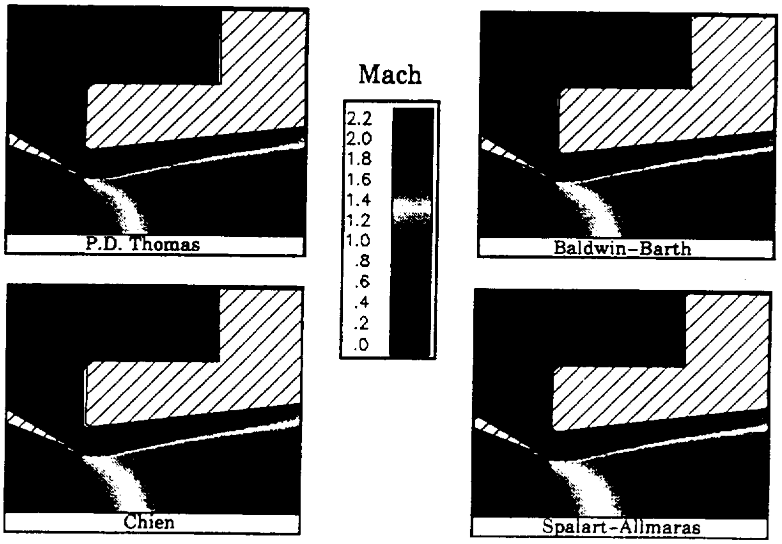
Four–Zone Grid for an Ejector Nozzle



Single Slot Ejector Analysis

NPR=14., Pts/Ptp=.34

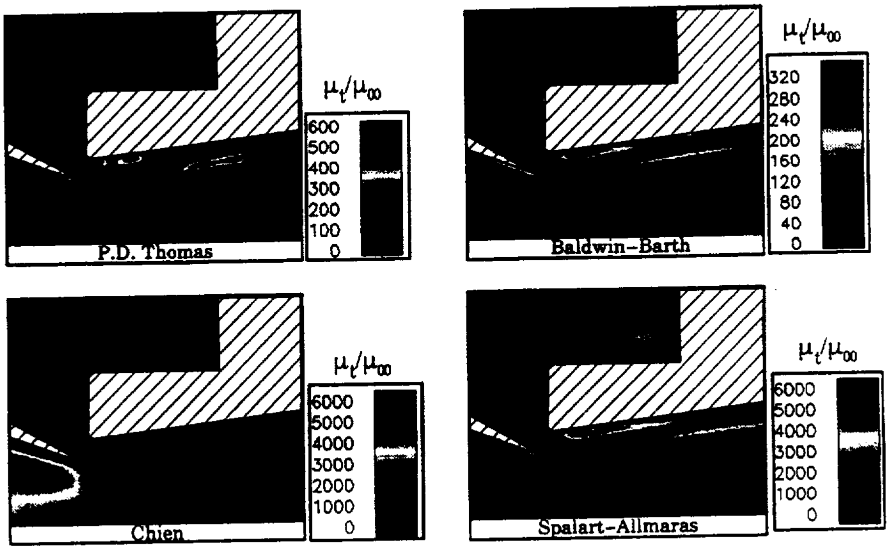
Mach Number Contours from Several Turbulence Models



Single Slot Ejector Analysis

NPR=14., Pts/Ptp=.34

Eddy Viscosity from Several Turbulence Models



Single-Slot Ejector Nozzle Analysis

$NPR = 14,\ P_{t_s}/P_{t_p} = 0.34$

$\mu_t/\mu_l \simeq 100$

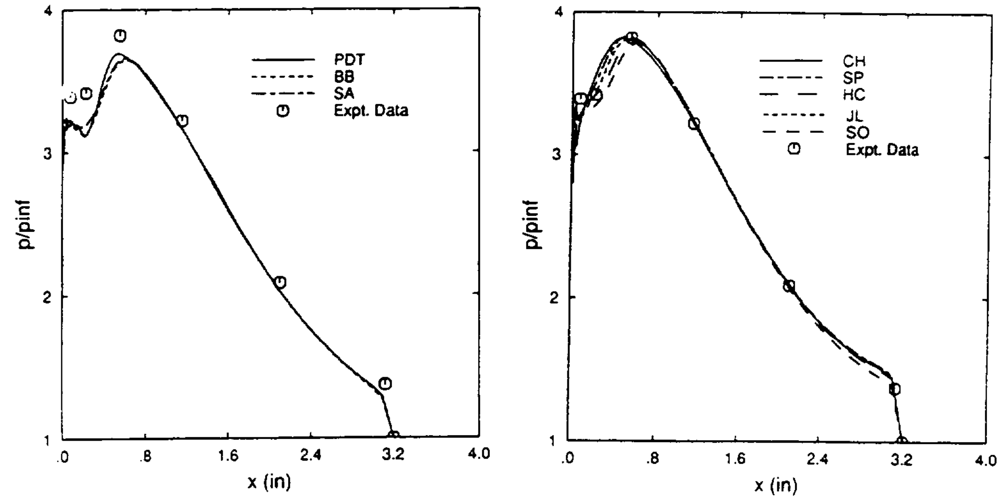
Comparison of Predicted Ejector Flow Rates

Model	W_s/W_p	% Error
Experiment	0.1010	–
Thomas/Baldwin-Lomax	0.1108	+9.7
Baldwin-Barth	0.1129	+11.8
Spalart-Allmaras	0.1146	+13.5
Chien $k-\epsilon$	0.1168	+15.6
Jones-Launder $k-\epsilon$	0.1126	+11.5
Speziale $k-\epsilon$	0.1127	+11.6
So $k-\epsilon$	0.1148	+13.7
Huang-Coakley $k-\epsilon$	0.1112	+10.1

Single Slot Ejector Nozzle

Surface Static Pressure Comparison with Experimental Data

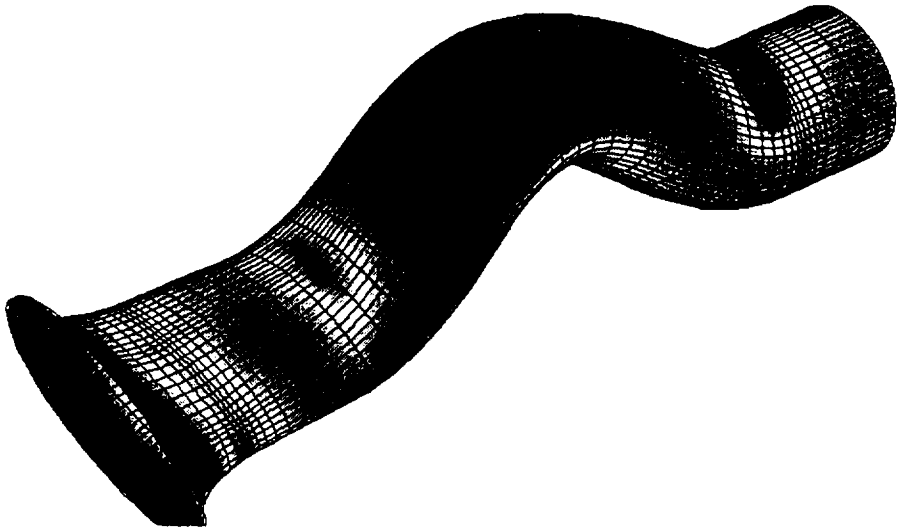
$NPR = 14.0,\ P_{t_s}/P_{t_p} = 0.34$



Offset Diffuser Analysis

Ae/At=1.6, L/D=4.5, Design Pressure Ratio

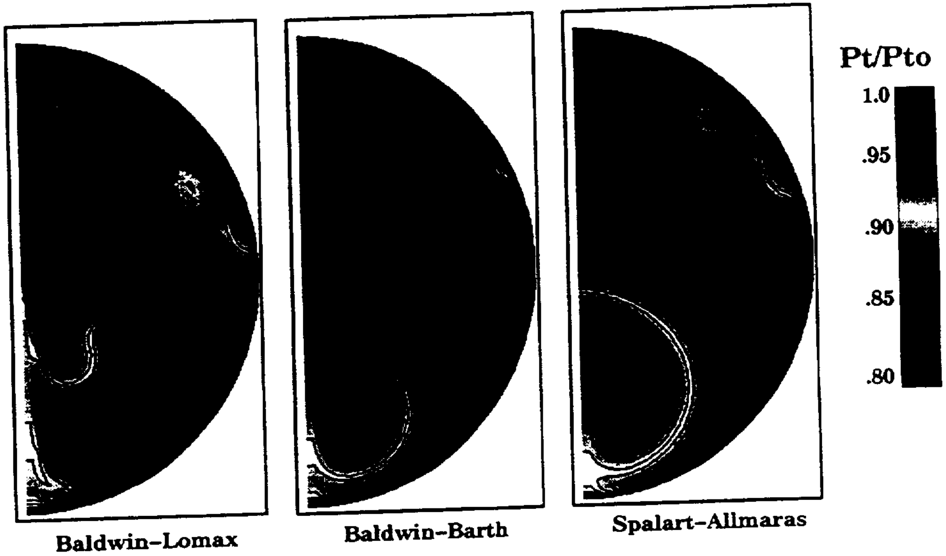
Surface Pressure and Computational Mesh



Offset Diffuser Analysis

Ae/At=1.6, L/D=4.5, Design Pressure Ratio

Comparison of Engine Face Total Pressures

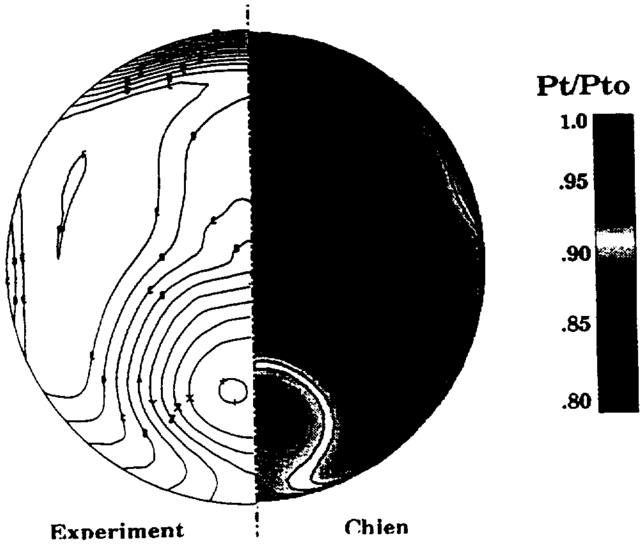


Baldwin-Lomax **Baldwin-Barth** **Spalart-Allmaras**

Offset Diffuser Analysis

Ae/At=1.6, L/D=4.5, Design Pressure Ratio

Comparison of Engine Face Total Pressures

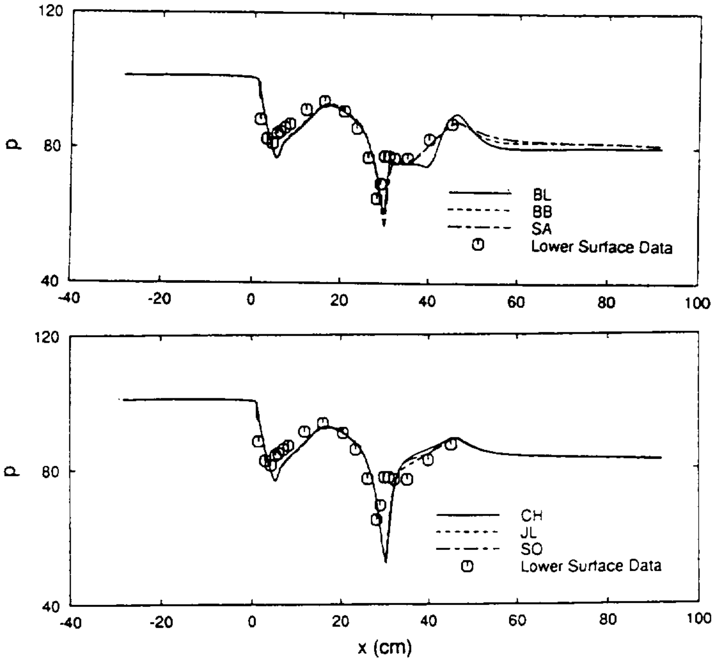


Experiment **Chien**

Offset Diffuser Analysis

Lower Centerline Surface Static Pressure

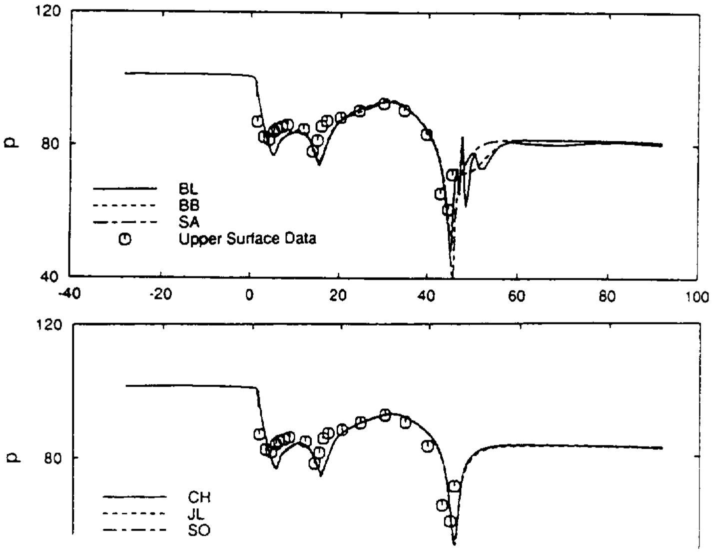
$A_e/A_t = 1.6$, $L/D = 4.5$, Design Pressure Ratio



Offset Diffuser Analysis

Upper Centerline Surface Static Pressure

$A_e/A_t = 1.6$, $L/D = 4.5$, Design Pressure Ratio



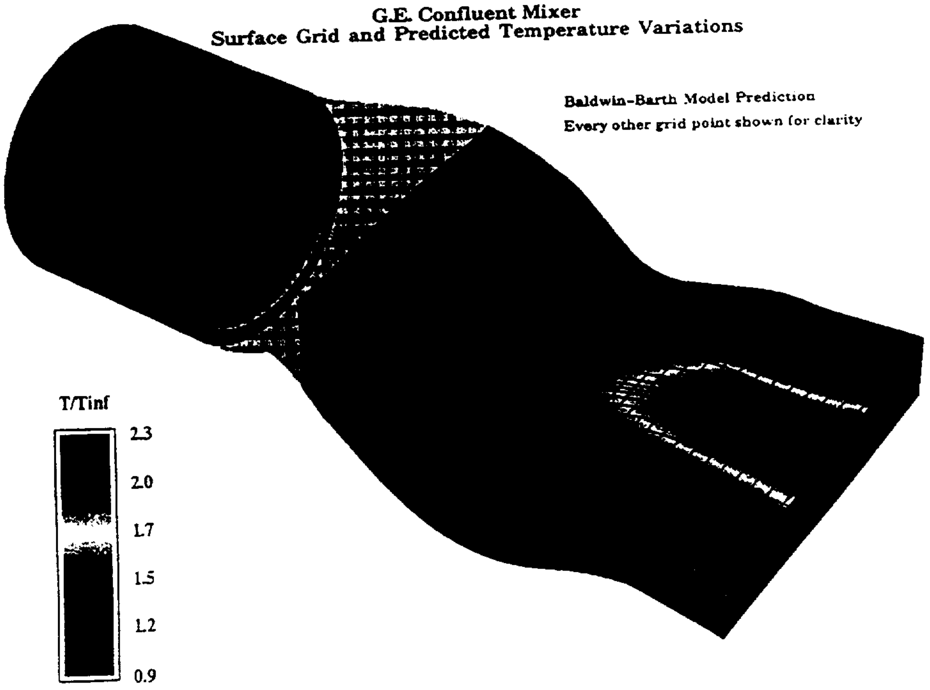
Three-Dimensional Highly Offset Diffuser

$A_e/A_t = 1.6$, $L/D = 4.5$, Design Pressure Ratio

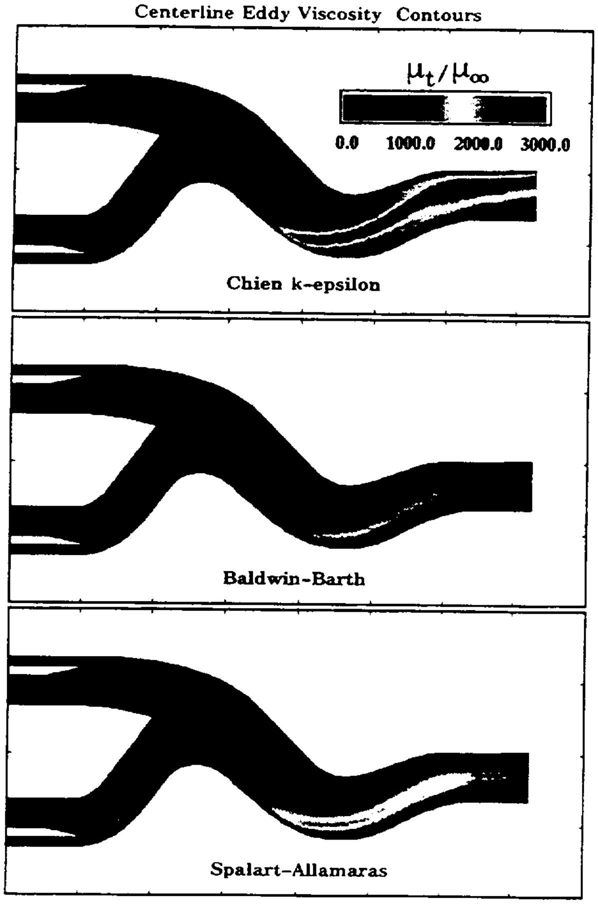
Comparison of Engine Face Parameters

Model	$P_{t_{avg}}/P_{t_\infty}$	$P_{t_{min}}/P_{t_\infty}$	$\frac{P_{t_{max}} - P_{t_{min}}}{P_{t_{avg}}}$
Experiment	0.958	0.890	0.114
Baldwin-Lomax	0.936	0.708	0.292
Baldwin-Barth	0.944	0.735	0.265
Spalart-Allmaras	0.955	0.860	0.140
Chien $k - \epsilon$	0.970	0.894	0.106
Jones-Launder $k - \epsilon$	0.966	0.896	0.104
So $k - \epsilon$	0.975	0.888	0.112

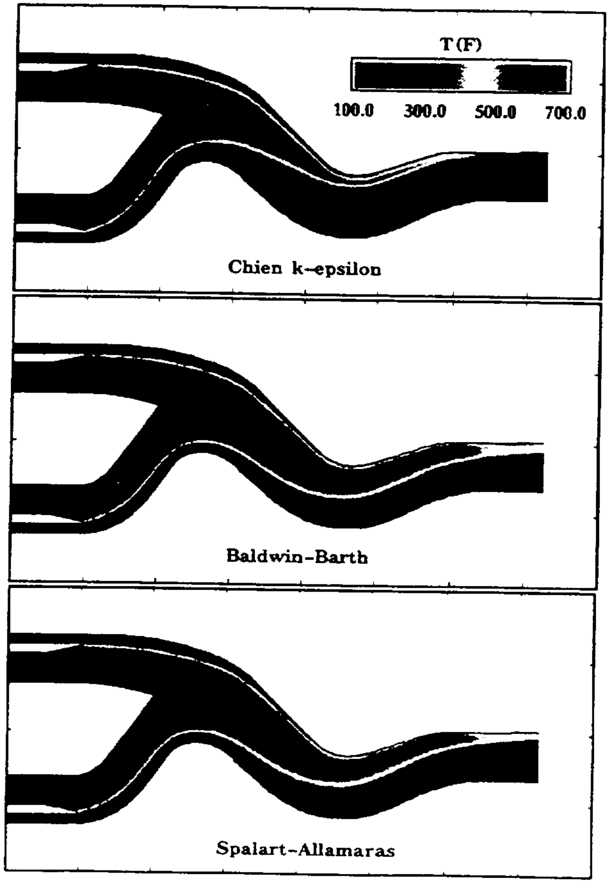
G.E. Confluent Mixer
Surface Grid and Predicted Temperature Variations



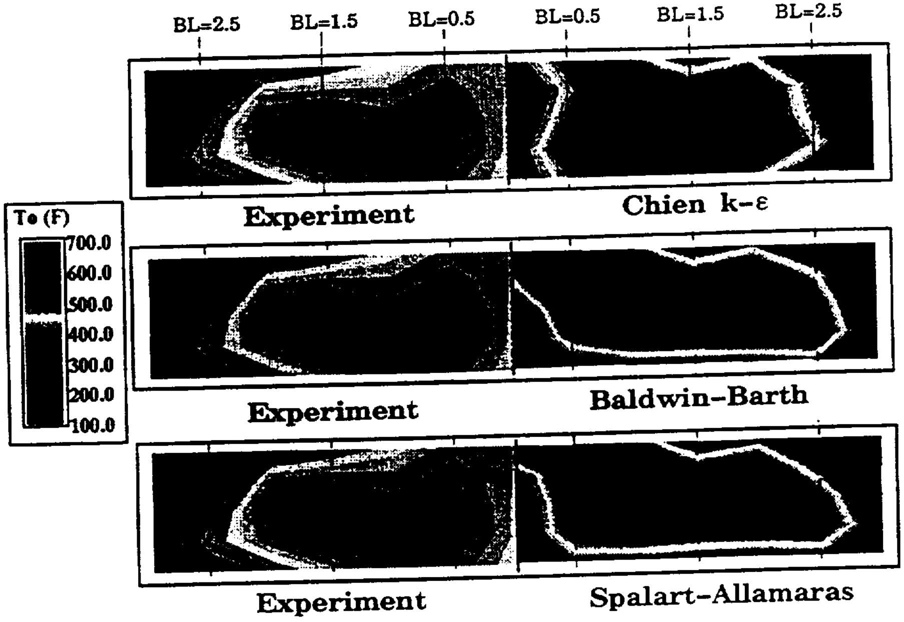
Centerline Eddy Viscosity Contours



Centerline Temperature Contours



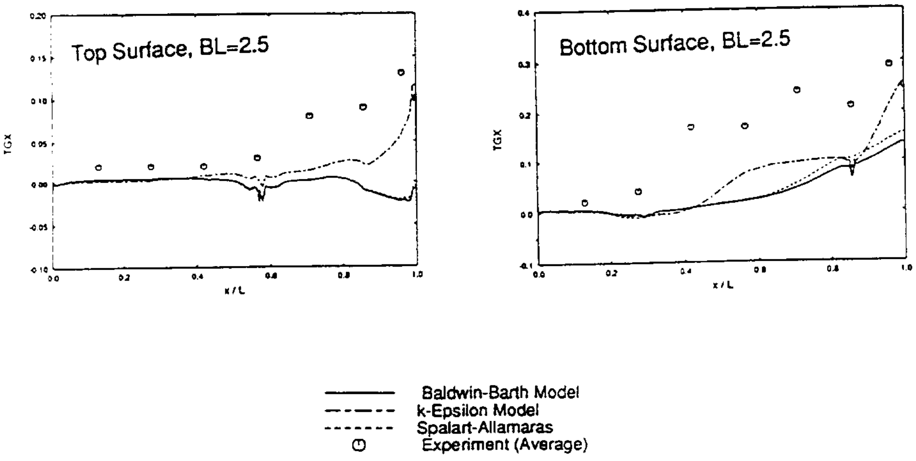
Comparison of Throat Total Temperatures



GE Slot Cooled Nozzle, Confluent Mixer

Surface Temperature Distributions,

$$TGX = (T_I - T_{I_{cold}})/(T_{I_{hot}} - T_{I_{cold}})$$



GE Slot Cooled Nozzle, Confluent Mixer

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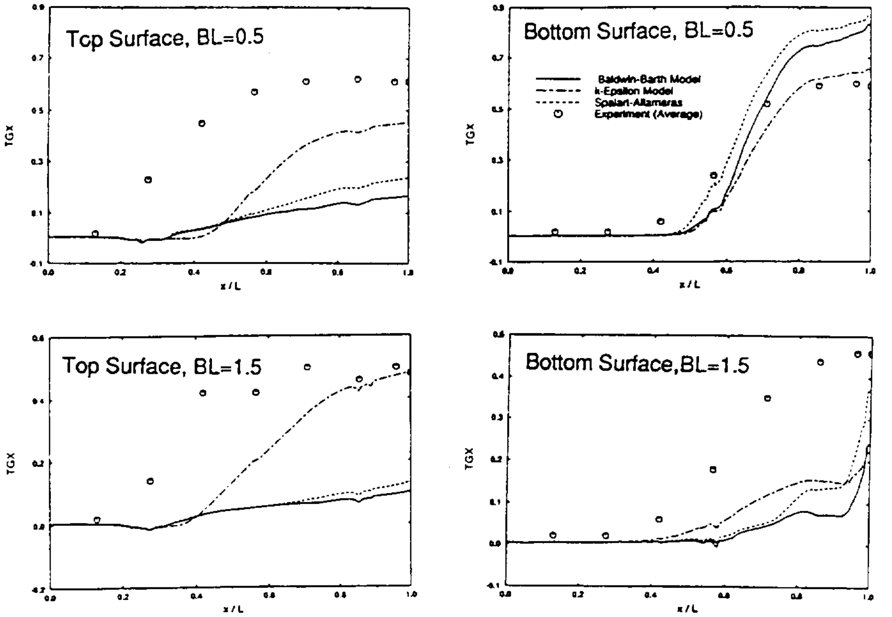

Summary of Turbulence Modeling at McDonnell Douglas Aerospace

- The one-equation models have replaced the algebraic models as the baseline turbulence models.
- The Spalart-Allmaras one-equation model consistently performs better than the Baldwin-Barth model, particularly in the log-layer and free shear layers. Also, the Spalart-Allmaras model in not grid dependent like the Baldwin-Barth model.
- No general turbulence model exists for all engineering applications.
- The Spalart-Allmaras one-equation model and the Chien $k-\epsilon$ models are the preferred turbulence models.
- Although the two-equation models often better predict the flowfield, they may take from two to five times the CPU time.
- Future directions are in further benchmarking the Menter blended $k-\omega/k-\epsilon$ and algorithmic improvements to reduce CPU time of two-equation model.