TURBULENCE MODEL DEVELOPMENT AND APPLICATION AT LOCKHEED FORT WORTH COMPANY

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Broad Range of Flow Problems of Interest

Wide Range of Flow Conditions:

- Subsonic – Hypersonic
- Internal – External – Store Separation
- Cruise – High Angle of Attack

Flows phenomena of Interest:

- Inlets/Diffusers
  - Streamwise Curvature
  - Shock/BL Interactions
  - Rectangular Duct → Circular
  - Leading Edge Separation - Cowl Lips
  - Separation Induced Unstart
- Nozzles
  - Entrainment
  - Round → Rectangular Duct
  - High Speed Shear Layers
  - Film cooling, Liners, Vanes
  - Swirl
- External Aerodynamics
  - Vortex
  - Leading Edge Separation
  - Shock/BL Interactions
  - 3D Boundary Layers
  - Wakes

The CFD Environment at Lockheed Fort Worth Company

Most codes developed or highly modified in house

General grid generation and solvers for diverse applications

Structured and unstructured solvers

Computational efficiency important

- Complex geometries, many gridpoints
- Large arrays of flow conditions

Requirements for Turbulence Models

Turbulence Modeling Priorities for Industrial Application

- Validation
  - High accuracy for attached flows
  - Reasonable accuracy for all flows
  - High confidence level
- Computational efficiency
- Robust for complex geometries
- Transitional modeling capability

To obtain acceptable accuracy, propulsion flows demand more sophisticated turbulence models than do external aerodynamic flows

The k - kl and k - l Two Equation Turbulence Models

Advantages of using kl or l instead of ε or ω

kl and l equations are easier to resolve numerically than ε equation

Dissipation Length Scale is an integral length scale

- Can derive equation for volume integral of two point correlation function.
- Theoretical ε equation is dominated by small scales

k - kl and k - l agree better with compressible boundary layer data than does $k - \varepsilon$

Disadvantage - current formulation requires calculation of distance to walls

<u>k - kl model</u>

- Includes unique, consistent wall function
- Accurate for transonic flows

<u>k - l model</u>

- Derived from k - kl model - identical in high Re turbulence
- Near wall model simulates k in viscous sublayer

The k – kl Model Wall Function

Wall layer model derived from and consistent with the k – kl model

- Assume convection in momentum, energy and turbulent kinetic energy equations to be negligible
- Boundary layer approximation

Match velocity, k and l at first grid point in Navier – Stokes solution

First grid point can be in viscous sublayer, buffer or logarithmic region

Boundary conditions on k and l simple for k – kl model

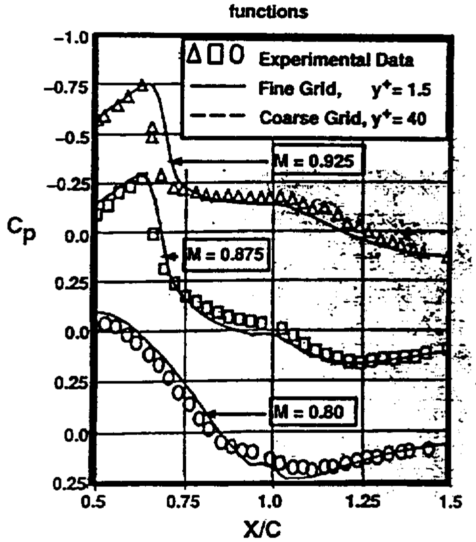
Advantages of wall functions

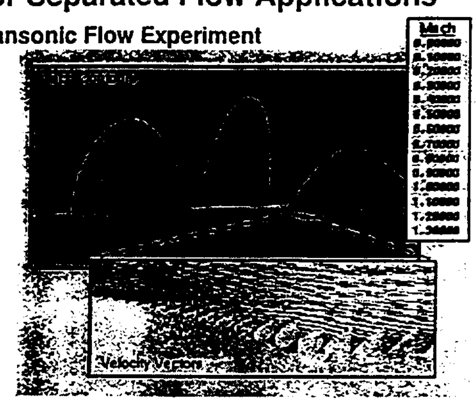
- Reduces number of necessary grid points
- Reduces number of iterations to converge steady state solution 60 – 90%

Wall Functions are Accurate for Separated Flow Applications

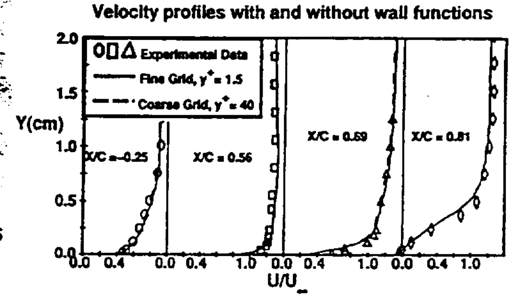
Axisymmetric Bump, Transonic Flow Experiment

Accurate predictions with and without wall functions





Velocity profiles with and without wall functions



The k – l Model with Near Wall Model

kl equation is transformed exactly to an l equation

Advantages of k – l formulation

- **l is linear near wall, κl nonlinear and very small**
- **Near wall damping terms disappear**
- **Production term drops out with current choice of constants**

k – l model includes:

- **Transitional flow modeling**
- **Compressibility corrections**

Modeling of details of k profile near wall important for hypersonic flows

- **Magnitude of normal stress term comparable to static pressure**
- **Near wall density variations large**

l Equation Much Easier to Resolve than ε Equation

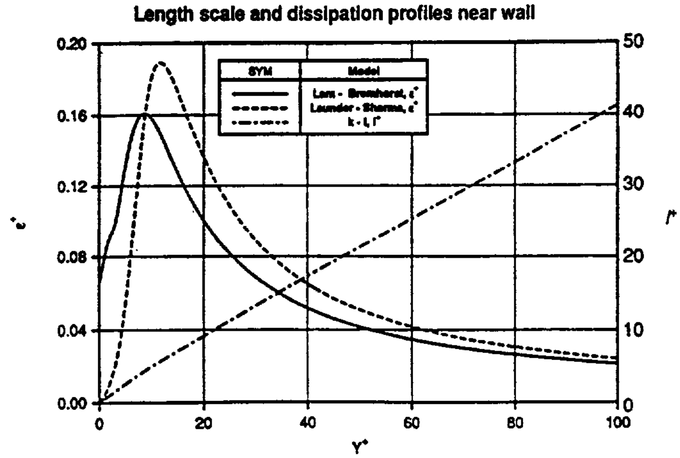
ε equation requires fine grid from wall to y^+ of 20 to resolve peak

•Exclusion of near wall viscous dissipation term aggravates problem

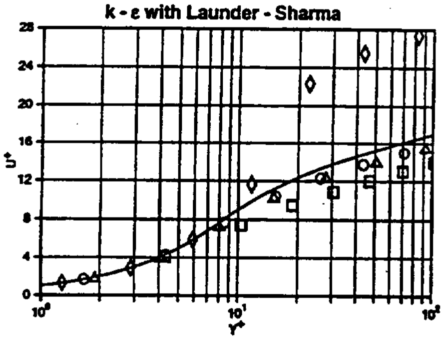
•Logarithmic region, $\varepsilon \propto 1/y$

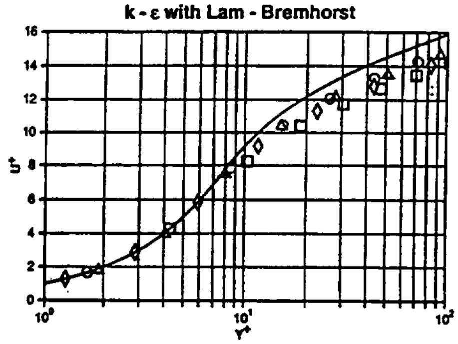
***l* equation is nearly linear near wall - much less sensitive to grid resolution**

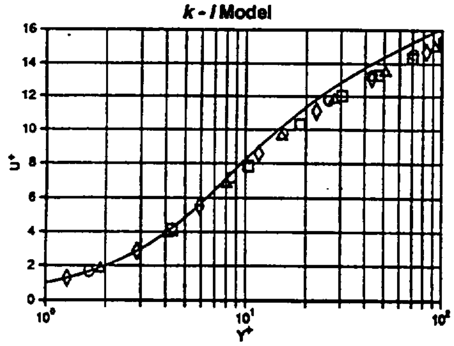
Length scale and dissipation profiles near wall



Resolution Study with k - ε and *k* - *l* Models







Symbol	Number of Grid Points	Stretching Rate from wall	Y^+, first grid point
———	151	1.04	0.033
□	11	1.4	4.3
○	11	1.6	1.65
△	11	1.8	0.67
◊	11	1.9	0.44

Sample Applications:

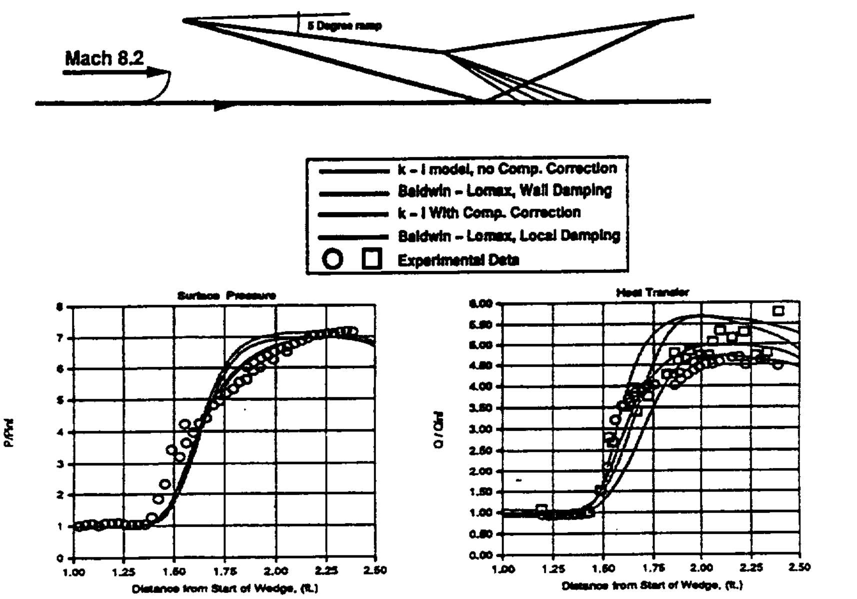
Mach 8 Shock Wave Turbulent Boundary Layer Interactions

F–16 Inlet Derivitive, Isolated Duct Study

Multi–slot Ejector

F110 Nozzle Drag Reduction Study

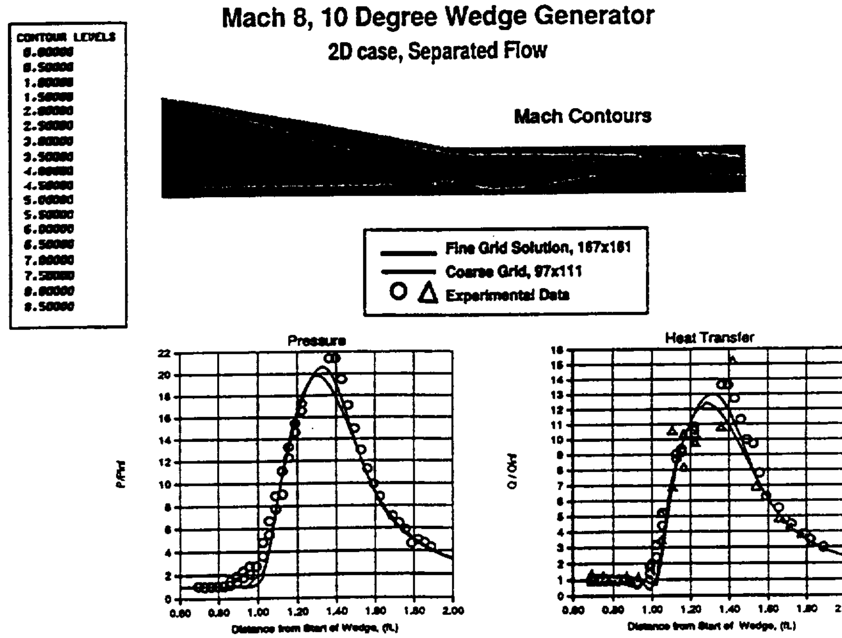
k – l Model With Compressibility Correction gives Best Prediction For Mach 8 Shock Boundary Layer Interaction

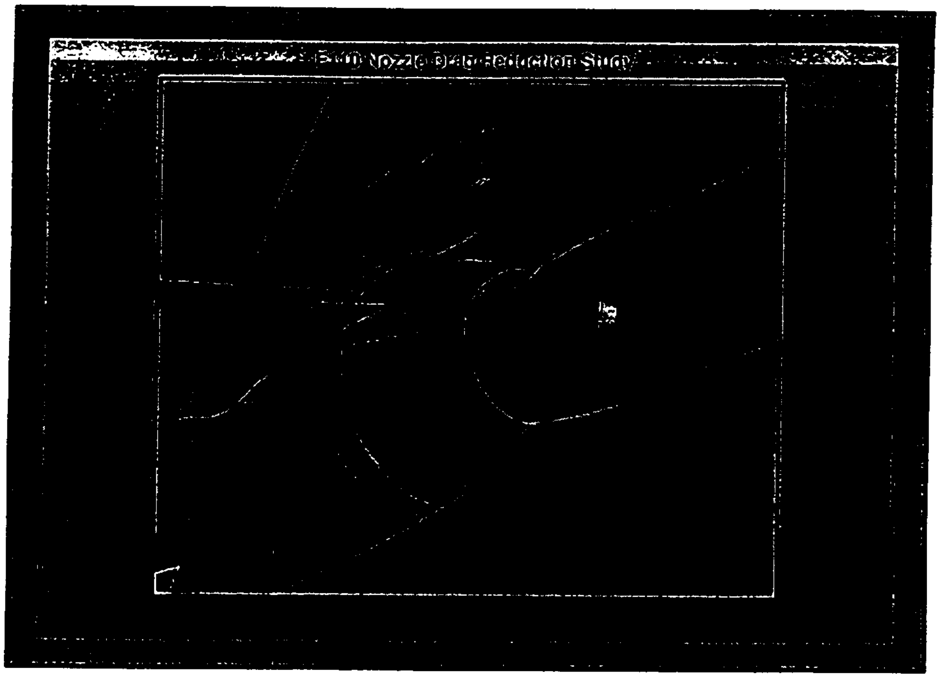


The k – l Model Predicts Turbulent Shock – Wave Boundary Layer Interaction Well

Mach 8, 10 Degree Wedge Generator

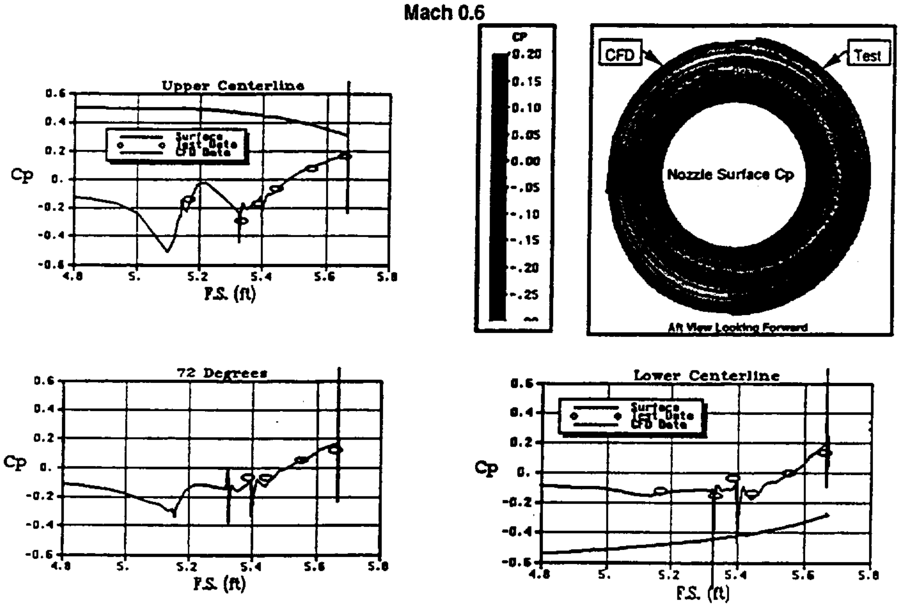
2D case, Separated Flow



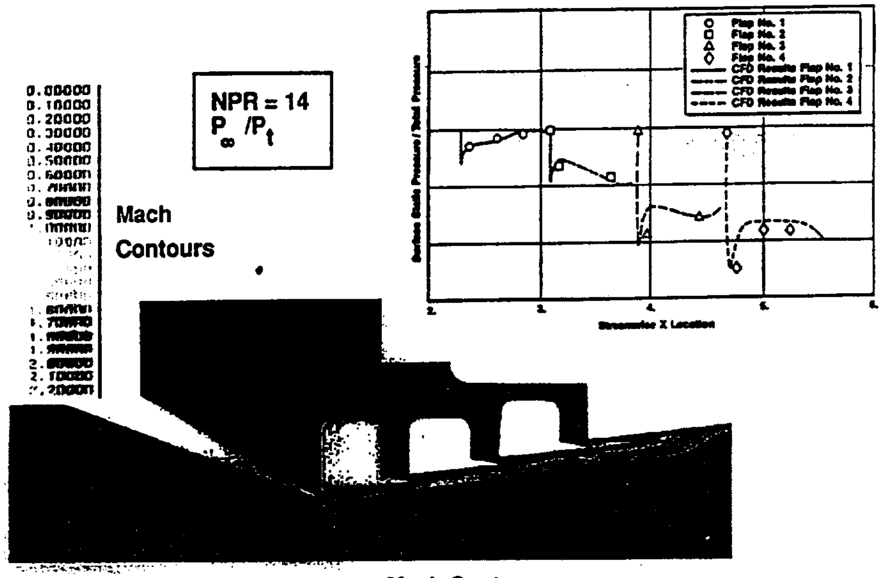


Afterbody/Nozzle Pressure Distributions Match Test Data

Mach 0.6



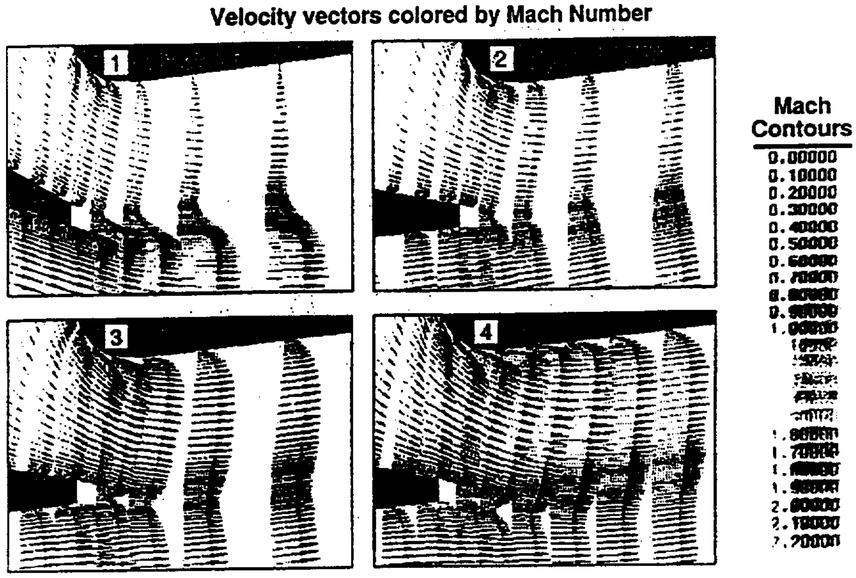
Good Predictions of Multi - Slot Ejector Obtained with k - kl Model



Mach Contours

k - kl Model Predicts Entrainment Effects Near Slots

Velocity vectors colored by Mach Number



Summary

Computationally efficient k – l and k – kl models have been developed and implemented at Lockheed Fort Worth Company

Many years of experience applying two equation turbulence models to complex 3D flows for design and analysis