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
- Nozzles
  - Entrainment
  - Round – Rectangular Duct
  - High Speed Shear Layers
- External Aerodynamics
  - Vortex
  - Leading Edge Separation
  - Shock/BL Interactions

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 - ε

Disadvantage - current formulation requires calculation of distance to walls

**k - kl model**
- Includes unique, consistent wall function
- Accurate for transonic flows

**k - l model**
- 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 I 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 I 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 – I Model with Near Wall Model

kl equation is transformed exactly to an I equation

Advantages of k – I formulation

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

k – I 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

/ 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, ε = 1/y

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

![Graph showing Length scale and dissipation profiles near wall](Image)
Resolution Study with \( k - \varepsilon \) and \( k - l \) Models

Sample Applications:

Mach 8 Shock Wave Turbulent Boundary Layer Interactions

F-16 Inlet Derivative, Isolated Duct Study

Multi-slot Ejector

F110 Nozzle Drag Reduction Study
The $k-l$ Model Predicts Turbulent Shock – Wave Boundary Layer Interaction Well

Mach 8, 10 Degree Wedge Generator
2D case, Separated Flow

The $k-l$ Model Predicts Turbulent Shock – Wave Boundary Layer Interaction Well
Afterbody/Nozzle Pressure Distributions Match Test Data
Mach 0.6

Upper Centerline

72 Degrees

Lower Centerline
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 $k-I$ and $k-I$ 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.