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 \( \varepsilon \) or \( \omega \)

- kl and l equations are easier to resolve numerically than \( \varepsilon \) equation
- Dissipation Length Scale is an integral length scale
  - Can derive equation for volume integral of two point correlation function.
  - Theoretical \( \varepsilon \) 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

<table>
<thead>
<tr>
<th>k - kl model</th>
<th>k - l model</th>
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<tbody>
<tr>
<td>• Includes unique, consistent wall function</td>
<td>• Derived from k - kl model - identical in high Re turbulence</td>
</tr>
<tr>
<td>• Accurate for transonic flows</td>
<td>• Near wall model simulates k in viscous sublayer</td>
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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 – l Model with Near Wall Model

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, kl 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

/ 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
Resolution Study with $k - \varepsilon$ and $k - I$ Models

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Number of Grid Points</th>
<th>Stretching Rate from wall</th>
<th>$y^*$, first grid point</th>
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<tr>
<td></td>
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<td>0.033</td>
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<td>1.4</td>
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<td>1.9</td>
<td>0.44</td>
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</tbody>
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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
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

Fine Grid Solution, 187x181
Coarse Grid, 97x111
Experimental Data
Afterbody/Nozzle Pressure Distributions Match Test Data

Mach 0.6

Upper Centerline

Cp

-0.6

-0.4

-0.2

0

0.2

0.4

-4.8

5.0

5.2

5.4

5.6

F.S. (R)

72 Degrees

Cp

-0.6

-0.4

-0.2

0

0.2

0.4

-4.8

5.0

5.2

5.4

5.6

F.S. (R)

Lower Centerline

Cp

-0.6

-0.4

-0.2

0

0.2

0.4

-4.8

5.0

5.2

5.4

5.6

F.S. (R)
Good Predictions of Multi-Slot Ejector Obtained with $k-kl$ Model

$NPR = 14 \frac{P_\infty}{P_1}$

Mach Contours

$k-kl$ Model Predicts Entrainment Effects Near Slots

Velocity vectors colored by Mach Number

Mach Contours
Summary

Computationally efficient \( k - 1 \) 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.