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
- Leading Edge Separation – Cowl Lips
- Separation Induced Unstart
- Film cooling, Liners, Vanes
- Swift
- 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 $\epsilon$ or $\omega$

- $kl$ and $l$ equations are easier to resolve numerically than $\epsilon$ equation
- Dissipation Length Scale is an integral length scale
  - Can derive equation for volume integral of two point correlation function.
  - Theoretical $\epsilon$ equation is dominated by small scales
- $k - kl$ and $k - l$ agree better with compressible boundary layer data than does $k - \epsilon$

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 $l$ 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

![Velocity profiles with and without wall functions](image)

![Cp profiles](image)
The $k - I$ Model with Near Wall Model

$kI$ equation is transformed exactly to an $I$ equation

Advantages of $k - I$ formulation

- $I$ is linear near wall, $kI$ 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

$I$ Equation Much Easier to Resolve than $\varepsilon$ Equation

$\varepsilon$ equation requires fine grid from wall to $y^+$ of 20 to resolve peak
- Exclusion of near wall viscous dissipation term aggravates problem
- Logarithmic region, $\varepsilon = 1/y$

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

![Graph showing length scale and dissipation profiles near wall]
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 $k - 1$ Model With Compressibility Correction gives Best Prediction For Mach 8 Shock Boundary Layer Interaction

The $k - 1$ Model Predicts Turbulent Shock - Wave Boundary Layer Interaction Well

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

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Afterbody/Nozzle Pressure Distributions Match Test Data

Mach 0.6

Upper Centerline

Nozzle Surface Cp

72 Degrees

Lower Centerline

At Near Leading Edge
Good Predictions of Multi-Slot Ejector Obtained with k-kl Model

\[ \text{NPR} = \frac{P_\infty}{P_t} \]

Mach Contours

k-kl Model Predicts Entrainment Effects Near Slots

Velocity vectors colored by Mach Number

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Summary

Computationally efficient $k - \ell$ 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.