TURBULENCE MODELING NEEDS OF COMMERCIAL CFD CODES: COMPLEX FLOWS IN THE AEROSPACE AND AUTOMOTIVE INDUSTRIES

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CONTENT OF PRESENTATION

• STAR-CD: COMPUTATIONAL FEATURES
• STAR-CD: TURBULENCE MODELS
• COMMON FEATURES OF INDUSTRIAL COMPLEX FLOWS
• INDUSTRY-SPECIFIC CFD DEVELOPMENT REQUIREMENTS
• INDUSTRIAL COMPLEX FLOWS: APPLICATIONS & EXPERIENCES
  - FLOW IN ROTATING DISC CAVITIES
  - DIFFUSION HOLE FILM COOLING
  - INTERNAL BLADE COOLING
  - EXTERNAL CAR AERODYNAMICS
• CONCLUSION: TURBULENCE MODELING NEEDS

STAR-CD: COMPUTATIONAL FEATURES

• BODY-FITTED NON-ORTHOGONAL COORDINATE SYSTEM
• UNSTRUCTURED COMPUTATIONAL MESH, DIFFERENT CELL TOPOLOGIES, IMBEDDED MESH REFINEMENT, DISCONTINUOUS MESH INTERFACE, MOVING BOUNDARY AND INTERNAL Interfaces
• PRIMITIVE VARIABLE, SELF-ADAPTIVE ELLIPTIC-HYPERBOLIC PRESSURE CORRECTION METHOD
• COLLOCATED-VARIABLE ARRANGEMENT
• EULER-IMPLICIT TEMPORAL INTEGRATION
• UD, CD, LUD, SFCD SPATIAL DISCRETIZATION, WITH BLENDING CAPABILITY
STAR-CD: TURBULENCE MODELS

- TWO-EQUATION MODEL
  - STANDARD $k$-$\varepsilon$ WITH CORRECTIONS FOR BULK DILATATION AND BUOYANCY
  - HIGH REYNOLDS NO. RNG BASED $k$-$\varepsilon$ MODEL

- TWO-ZONE (TWO-LAYER) MODEL
  - HIGH REYNOLDS NO.: $k$-$\varepsilon$ VARIANTS
  - LOW REYNOLDS NO.: $k$-$\varepsilon$ VARIANTS, PRANDTL MIXING LENGTH MODEL

STAR-CD: TURBULENCE MODELS

- REYNOLDS STRESS TRANSPORT MODEL
  - TRANSPORT EQUATIONS FOR CARTESIAN STRESS TENSOR IN NON-ORTHOGONAL COORDINATE SYSTEM, ON NON-STRUCTURED MESH
  - LAUNDER, RODI, REECE (1975) FORMULATION WITH LAUNDER (1989) MODEL CONSTANTS
  - GIBSON & LAUNDER (1978) WALL REFLECTION MODEL
Driver & Seegmiller Backward Facing Step
Flow Domain = -0.1 to 3.1
Mesh = 105 (Axial) x 45 (Radial)
Driver & Seegmiller Backward Facing Step
Data inlet B.C.; No Wall Damping Func.
Location 50X = 1.5
COMMON FEATURES OF INDUSTRIAL COMPLEX FLOWS

- THREE DIMENSIONAL WITH MULTIPLE FLOW "COMPLEXITIES"
  - BODY-FORCE FIELDS
  - STREAM SURFACE CURVATURE
  - STRONG PRESSURE GRADIENTS
  - COMPRESSIBILITY EFFECTS
  - LAMINAR-TURBULENT TRANSITION
  - COMBUSTION, SHOCK, MULTIPHASE, NON-NEWTONIAN
- LARGE SCALE DOMAIN AND COMPLEX GEOMETRIC CONFIGURATION
- IRREGULAR, UNSTRUCTURED COMPUTATIONAL MESH
- SPATIAL RESOLUTION DIFFICULT TO ACHIEVE ON $O(10^5 - 10^6)$ MESH CELLS
- INSUFFICIENT AND UNCERTAIN EXPERIMENTAL DATA FOR TURBULENCE MODEL VALIDATION/IDENTIFICATION OF DEFICIENCIES
INDUSTRY-SPECIFIC CFD DEVELOPMENT REQUIREMENTS

• AUTOMOTIVE INDUSTRY
  - EFFICIENT COMPLEX-GEOMETRY, MOVING-BOUNDARY CAPABILITIES
  - MEMORY/SOLUTION PERFORMANCE FOR LARGE SCALE DOMAIN CFD SIMULATION
  - DIAGNOSTIC/COMPARATIVE EVALUATION OBJECTIVES
  - GEOMETRIC FIDELITY AND SPATIAL RESOLUTION ARE PRIMARY ACCURACY FACTORS

• AEROSPACE INDUSTRY
  - REGULAR AND SMALL-SCALE FLOW DOMAIN (BENCHMARK EXPERIMENTAL MODELS)
  - DESIGN/PERFORMANCE OPTIMIZATION OBJECTIVES
  - NUMERICAL AND TURBULENCE MODEL ACCURACY IMPORTANT
  - REQUIREMENTS
    - HEAT TRANSFER
    - LOW REYNOLDS NO. FLOW
    - BODY FORCE FIELDS
Figure 1: Exterior boundary conditions for W202 40 kph analysis.
W202 UNDERHOOD FLOW ANALYSIS
CASE 3: 40 mph SIMULATION
Velocity near the surface of the vehicle.

W202 UNDERHOOD FLOW ANALYSIS
CASE 3: 40 mph SIMULATION
Temperature of the environment.
# APPLICATIONS & EXPERIENCES

<table>
<thead>
<tr>
<th>APPLICATION (DATA)</th>
<th>FLOW COMPLEXITY</th>
<th>TURBULENCE MODEL</th>
<th>FINDINGS</th>
<th>T.M. NEEDS</th>
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<tbody>
<tr>
<td>ROTATING DISC CAVITY¹</td>
<td>• FORCE FIELD</td>
<td>• k-ε</td>
<td>• EKMAN LAYER RESOLVED</td>
<td>• RSTM + SUITABLE 2 LAYER</td>
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<td>• WALL EFFECT</td>
<td>• 2 LAYER k-ε</td>
<td>• FAIR PRESSURE DROP</td>
<td>• LOW Re RSTM</td>
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<td>• EXCESSIVE E.V.</td>
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<td>DIFFUSION HOLE FILM COOLING²</td>
<td>• JET-CROSS FLOW</td>
<td>• k-ε</td>
<td>• JET SEPARATION SENSITIVE TO MESH</td>
<td>• RSTM + SUITABLE 2 LAYER</td>
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<td>• WALL ANISOTROPY</td>
<td>• RNG, k-ε</td>
<td>TOPOLOGY/RESOLUTION</td>
<td>• LOW Re RSTM</td>
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<td></td>
<td></td>
<td>• 2 LAYER k-ε</td>
<td>• POOR SPANWISE SPREAD</td>
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¹ GRABER et al (1987)  

**COMPRESSOR DRUM TEST RIG STAR-CD CONJUGATE HEAT TRANSFER MODEL**

[Diagram of the Compressor Drum Test Rig]

- **Upstream Endwall**
- **Downstream Endwall**
- **Bore Tube**
- **Disk 1**
- **Disk 5**
- **Axis of Rotation**
HALF-CAVITY TEST MODEL: MESH IS TYPICAL FOR MULT-CAVITY MODEL

disk dim (r = 11.0 in.)
coolant injection location (via)

72 cells (1.250 in.)
symmetry plane

last heater wall cell (0.0000618 in. thick)
disk bore (r = 4.0 in.)

exhaust (outlet)

bore tube O.D. (r = 3.0 in.)

disk face

test heater wall cell (0.0000618 in. thick)

Compressor Drum Test Rig Cold Flow Benchmark Analysis
Secondary Flow

14-Jun-93
VELOCITY
COMPONENTS U W
FTSCEC
PSYS=2
LOCAL MX= 36.44
LOCAL MNY 0.2782E-01
"PRESENTATION GRID"

36.44
33.84
31.24
28.64
26.04
23.44
20.84
18.24
15.64
13.04
10.43
7.831
5.230
2.629
0.2782E-01
Compressor Drum Test Rig Cold Flow Benchmark Analysis
Secondary Flow in Cavity 2
Velocity Vectors at r = 7.45 inches

14-Jun-93
VELOCITY COMPONENTS U W FT/SEC
PSYS= 2
LOCAL MAX= 22.30
LOCAL MIN= 0.4491

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<th>Velocity Components</th>
<th>ft/sec</th>
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<tbody>
<tr>
<td>U</td>
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CAVITY 2: PRESSURE DROP

Dimensionless Pressure Drop

- STAR-CD Model
- Test Data
- Forced Vortex
- Free Vortex

Dimensionless Radius Ratio

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CAVITY 4: PRESSURE DROP

Dimensionless Pressure Drop

- STAR-CD Model
- Test Data
- Forced Vortex
- Free Vortex

Mesh = 330000 fluid cells
Two-Layer mesh
CFD Discrete Hole Film Cooling Verification Study
Simulation of experiment of Goldstein, et. al. [1968]; Blowing ratio M = 0.5
Velocity vectors on spanwise planes; 2-layer model.

CFD Discrete Hole Film Cooling Verification Study
Simulation of experiment of Goldstein, et. al. [1968]; Blowing ratio M = 0.5
Temperature contours on spanwise planes; 2-layer model.
EXPERIMENTS OF GOLDS'TEIN ET AL., 1968
COMPARISON OF FILM COOLING EFFECTIVENESS
M = 0.5 - Mesh III.
APPLICATIONS & EXPERIENCES (cont’d)

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<tr>
<td>INTERNAL BLADE COOLING³</td>
<td>• FORCE FIELD</td>
<td>• k-ε</td>
<td>• DEPENDENCE ON MESH RESOLUTION</td>
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<td>EXTERNAL CAR AERO-DYNAMICS⁴</td>
<td>• B.L. STRUCTURE INTERACTION</td>
<td>• k-ε</td>
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<td>RSTM</td>
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<td>• COMPLEX WAKE</td>
<td>• RNG k-ε</td>
<td>• GOOD C_d</td>
<td>LOW Re RSTM</td>
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<td>• 2 LAYER k-ℓ</td>
<td>• POOR LIFT</td>
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³GE AIRCRAFT ENGINES [ABUAF & KERCHER (1991)]
⁴10 FORD 1/4 SCALE MODELS IN WIND TUNNEL TEST [WILLIAMS et al (1994)]
Figure 4. Leading edge channel heat transfer distribution with distance from the inlet. Comparison of model turbulent convex surface maximum, minimum and average measurements with blade CFD average predictions.
WIND TUNNEL AERODYNAMICS STUDY OF NOTCHBACK TEST SHAPE
KE RESULTS - KE TURBULENCE MODEL WITH LUD
VELOCITY MAGNITUDE NEAR THE VEHICLE

VIEW FROM REAR
EXPERIMENTAL RESULTS
COMPARISON OF EXPERIMENTAL AND COMPUTATIONAL LIFT COEFFICIENTS
K Epsilon TURBULENCE MODEL - *** INITIAL RESULTS ***

EXPERIMENTAL RESULTS
COMPARISON OF EXPERIMENTAL AND COMPUTATIONAL DRAG COEFFICIENTS
K Epsilon TURBULENCE MODEL - *** INITIAL RESULTS ***
CONCLUSIONS: TURBULENCE MODELING
IMMEDIATE NEEDS

• NEAR-WALL TURBULENCE
  - ECONOMICAL, ROBUST LOW REYNOLDS
    NUMBER 2 EQ. EVM’s AND RSTM
  - A GENERAL AND VERSATILE NEAR-WALL
    TREATMENT FOR RSTM

• RSTM MODEL
  - ALTERNATIVE CLOSURE OF THE WALL
    REFLECTION COMPONENT, WITHOUT NEED OF
    WALL TOPOGRAPHY PARAMETERS

• EDDY-VISCOSITY MODELS
  - EXTENSION OF THE NON-LINEAR k-ε TO
    INCORPORATE FORCE-FIELD EFFECTS

• BENCHMARKING
  - A RELIABLE DATABASE OF BENCHMARK SET OF
    REPRESENTATIVE COMPLEX FLOWS
  - BENCHMARK PERFORMANCE CLASSIFICATION
    OF VARIOUS EVM’s (k-ε, k-ω, RNG AND NON-
    LINEAR k-ε, MULTISCALE EVM’s) AND RSTM
    CLOSURE VARIANTS

CONCLUSIONS: TURBULENCE MODELING
PROGRAM NEEDS

• A LARGER VIEW OF THE RSTM DEVELOPMENT
  TOWARDS IMPLEMENTATION IN GENERAL
  COORDINATE, COMPLEX GEOMETRY DOMAIN,
  UNSTRUCTURED CFD METHOD

• A BROADER APPLICATION OF DNS TO
  COMPLEX FLOWS TO ASSIST TURBULENCE
  MODEL DEVELOPMENT/OPTIMIZATION

• WELL-POSED EXPERIMENTAL DATA,
  OBTAINED IN THE ORIGINAL OR REDUCED
  SCALE MODEL OF THE INDUSTRIAL
  COMPONENT FOR CFD VALIDATION

• COLLABORATIVE INDUSTRY-CFD
  RESEARCH/DEVELOPMENT PROGRAMS FOR
  EXPERIMENTATION - CFD VALIDATION
  (CALIBRATION) FOR SPECIFIC INDUSTRIAL
  APPLICATIONS