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°H to 37°H
Mesh = 105 (Axial) x 45 (Radius)

Legend

- Exp. data
- RS model
- KE model

Graph Plot
Frames
Driver & Seegmiller Backward Facing Step
Data Inlet B.C.; No Wall Damping Funct.
Location 50x = 1.5

Legend
- Exp. data
--- RS model
---- KE model
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 near the surface of the vehicle.
# 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>
</tr>
</thead>
<tbody>
<tr>
<td>ROTATING DISC CAVITY(^1)</td>
<td>FORCE FIELD • WALL EFFECT</td>
<td>• k-ε • 2 LAYER k-ε</td>
<td>• EKMAN LAYER RESOLVED • FAIR PRESSURE DROP • EXCESSIVE E.V.</td>
<td>• RSTM + SUITABLE 2 LAYER • LOW Re RSTM</td>
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<tr>
<td>DIFFUSION HOLE FILM COOLING(^2)</td>
<td>JET-CROSS FLOW • WALL ANISOTROPY</td>
<td>• k-ε • RNG, k-ε • 2 LAYER k-ε</td>
<td>• JET SEPARATION SENSITIVE TO MESH TOPOLOGY/RESOLUTION • POOR SPANWISE SPREAD</td>
<td>• RSTM + SUITABLE 2 LAYER • LOW Re RSTM</td>
</tr>
</tbody>
</table>

\(^1\) GRABER et al (1987)
\(^2\) GOLDSTEIN et al (1968), LIGRANI et al (1992)

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**COMPRESSOR DRUM TEST RIG**

STAR-CD CONJUGATE HEAT TRANSFER MODEL

[Diagram of a compressor drum test rig showing various components such as upstream and downstream endwalls, bow tube, disks, and axis of rotation]
HALF-CAVITY TEST MODEL: MESH IS TYPICAL FOR MULT-CAVITY MODEL

coolant injection location (viet)

72 cells (1.250 in.)
symmetry plane

test heat wall cell (0.00025918 in. thick)
disk bane (r = 4.0 in.)

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

14-Jun-93
VELOCITY COMPONENTS U W
FTIESC
PSYS= 2
LOCAL Mx= 36.44
LOCAL Mxy= 0.278E-01
"PRESENTATION GRID"

Compressor Drum Test Rig Cold Flow Benchmark Analysis
Secondary Flow
Compressor Drum Test Rig Cold Flow Benchmark Analysis
Secondary Flow in Cavity 2
Velocity Vectors at t = 7.45 inches

CAVITY 2: PRESSURE DROP

Dimensionless Pressure Drop
- STAR-CD Model
- Test Data
- Forced Vortex
- Free Vortex

Dimensionless Radius Ratio

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

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<tr>
<th>Velocity VELOCITY</th>
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<tr>
<td>FT/SEC</td>
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<tr>
<td>PSYS= 2</td>
</tr>
<tr>
<td>LOCAL MAX= 22.30</td>
</tr>
<tr>
<td>LOCAL MIN= 0.4491</td>
</tr>
<tr>
<td>22.30</td>
</tr>
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<td>21.21</td>
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<td>3.727</td>
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<td>2.635</td>
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<tr>
<td>1.542</td>
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<tr>
<td>0.4491</td>
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</table>
CAVITY 4: PRESSURE DROP

Dimensionless Pressure Drop

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

Dimensionless Radius Ratio

Refined mesh, \( M = 0.5 \), pipe grid abutting plate grid.
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
Temperature contours on spanwise planes ; 2-layer model.
EXPERIMENTS OF GOLSTEIN ET AL., 1968
COMPARISON OF FILM COOLING EFFECTIVENESS
M = 0.5: Mesh II.
### APPLICATIONS & EXPERIENCES (cont'd)

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</thead>
<tbody>
<tr>
<td>INTERNAL BLADE COOLING(^3)</td>
<td>• FORCE FIELD</td>
<td>• k-ε</td>
<td>• DEPENDENCE ON MESH RESOLUTION</td>
<td></td>
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<tr>
<td></td>
<td>• B.L. DISRUPTION</td>
<td></td>
<td>• GOOD ΔP, h</td>
<td></td>
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<tr>
<td>EXTERNAL CAR AERO-DYNAMICS(^4)</td>
<td>• B.L. STRUCTURE INTERACTION</td>
<td>• k-ε</td>
<td>• DEPENDENCE ON MESH RESOLUTION</td>
<td>• RSTM</td>
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<tr>
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<td>• COMPLEX WAKE</td>
<td>• RNG k-ε</td>
<td>• GOOD C(_D)</td>
<td>• LOW Re RSTM</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• 2 LAYER k-(\ell)</td>
<td>• POOR LIFT</td>
<td></td>
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</tbody>
</table>

\(^3\)GE AIRCRAFT ENGINES [ABUAF & KERCHER (1991)]

\(^4\)10 FORD 1/4 SCALE MODELS IN WIND TUNNEL TEST [WILLIAMS et al (1994)]
29 Aug 94
PRESSURE
NM$^2$
LOCAL MX= 4.427E+06
LOCAL MN= -2.719E-06

MAGNITUDE VELOCITY
M/SEC
PSYS 2
LOCAL MX= 314.6
LOCAL MN= 4.850
*PRESENTATION GRID*
Figure 4a Leading edge channel heat transfer distribution with distance from the inlet. Comparison of model turbulated convex surface maximum, minimum and average measurements with blade CFD average predictions.
THIRD GRID REDUCTION (3:1)
SECOND GRID REDUCTION (2:1)
WAKE REGION

FIRST GRID REDUCTION (2:1)

NOTCHBACK WIND TUNNEL AERODYNAMIC STUDY MODEL
COMPLETE MODEL DOMAIN

DGRID

NOTCHBACK WIND TUNNEL AERODYNAMICS STUDY OF NOTCHBACK TEST SHAPE
KE RESULTS - KE TURBULENCE MODEL WITH LID
VELOCITY MAGNITUDE NEAR THE VEHICLE

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

[Graph showing comparison of experimental and computational lift coefficients for different models using the K Epsilon turbulence model.]

EXPERIMENTAL RESULTS
COMPARISON OF EXPERIMENTAL AND COMPUTATIONAL DRAG COEFFICIENTS
K EPSILON TURBULENCE MODEL - "**INITIAL RESULTS**"

[Graph showing comparison of experimental and computational drag coefficients for different models using the K Epsilon turbulence model.]
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