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

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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 = -3'H to 3'H
Mesh = 105 (Axial) x 45 (Radius)

Legend

- Exp. data
- RS model
- KE model

Driver & Seegmiller Backward Facing Step
Data Inlet B.C.
Location X/H = 1.5
Driver & Seegmiller Backward Facing Step
Data Intet B.C.: No Wall Damping Fund.
Location 50+ = 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 - 10^8) MESH CELLS

- INSUFFICIENT AND UNCERTAIN EXPERIMENTAL DATA FOR TURBULENCE MODEL VALIDATION/IDENTIFICATION OF DEFICIENCIES

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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
### VELOCITY MAGNITUDE

<table>
<thead>
<tr>
<th>Velocity</th>
<th>Value</th>
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<tbody>
<tr>
<td>1.00</td>
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<td>13.00</td>
</tr>
<tr>
<td>1.07</td>
<td>12.00</td>
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<tr>
<td>1.09</td>
<td>11.25</td>
</tr>
<tr>
<td>1.11</td>
<td>10.50</td>
</tr>
<tr>
<td>1.13</td>
<td>0.750</td>
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</tr>
<tr>
<td>1.17</td>
<td>0.250</td>
</tr>
<tr>
<td>1.19</td>
<td>0.125</td>
</tr>
<tr>
<td>1.21</td>
<td>0.000</td>
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**W202 UNDERHOOD FLOW ANALYSIS**

CASE 3: 40 mph SIMULATION

Velocity near the surface of the vehicle.

### TEMPERATURE

<table>
<thead>
<tr>
<th>Temperature</th>
<th>Value</th>
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<tbody>
<tr>
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<tr>
<td>55.00</td>
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</tr>
<tr>
<td>50.00</td>
<td>70.00</td>
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<tr>
<td>40.00</td>
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<tr>
<td>35.00</td>
<td>40.00</td>
</tr>
<tr>
<td>30.00</td>
<td>30.00</td>
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</table>

**W202 UNDERHOOD FLOW ANALYSIS**

CASE 3: 40 mph SIMULATION

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## 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 CAVITY¹</td>
<td>FORCE FIELD</td>
<td>k-ε</td>
<td>EKMAN LAYER RESOLVED</td>
<td>RSTM + SUITABLE 2 LAYER</td>
</tr>
<tr>
<td></td>
<td>WALL EFFECT</td>
<td>2 LAYER k-ε</td>
<td>FAIR PRESSURE DROP</td>
<td>LOW Re RSTM</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>EXCESSIVE E.V.</td>
<td></td>
</tr>
<tr>
<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>
</tr>
<tr>
<td></td>
<td>WALL ANISOTROPY</td>
<td>RNG, k-ε</td>
<td>TOPOLOGY/RESOLUTION</td>
<td>LOW Re RSTM</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2 LAYER k-ε</td>
<td>POOR SPANWISE SPREAD</td>
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</tr>
</tbody>
</table>

¹ GRABER et al (1987)

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

![Diagram of Compressor Drum Test Rig](image)

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

disk dim (r = 11.0 in.)

coolant injection location (nail)

72 cells (1.250 in.)
symmetry plane

last near wall cell (0.0002591 in. thick)
disk bore (r = 4.0 in.)

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

disk face

25 cells (0.0218 in.)

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 r = 7.45 inches

CAVITY 2: PRESSURE DROP

Dimensionless Pressure Drop

- STAR-CD Model
- Test Data
- Forced Vortex
- Free Vortex
CAVITY 4: PRESSURE DROP

Dimensionless Pressure Drop

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

Reframed mesh, M = 0.5, pipe grid abutting plate grid.
Mesh = 330000 fluid cells
Two-Layer mesh

VIEW
1.00
1.00
1.00
ANGLE
0.00
DISTANCE
64.254
CENTER
258.461
78.577
118.614
HIDDEN PLOT
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 II.
### APPLICATIONS & EXPERIENCES (cont’d)

<table>
<thead>
<tr>
<th>APPLICATION (DATA)</th>
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<th>TURBULENCE MODEL</th>
<th>FINDINGS</th>
<th>T.M. NEEDS</th>
</tr>
</thead>
</table>
| INTERNAL BLADE COOLING³ | • FORCE FIELD  
• B.L. DISRUPTION | • k-ε | • DEPENDENCE ON MESH RESOLUTION  
• GOOD ΔP, h | |
| EXTERNAL CAR AERODYNAMICS⁴ | • B.L. STRUCTURE INTERACTION  
• COMPLEX WAKE | • k-ε  
• RNG k-ε  
• 2 LAYER k-ε | • DEPENDENCE ON MESH RESOLUTION  
• GOOD Cₐ  
• POOR LIFT | • RSTM  
• LOW Re RSTM |

³GE AIRCRAFT ENGINES [ABUAF & KERCHER (1991)]
⁴10 FORD 1/4 SCALE MODELS IN WIND TUNNEL TEST [WILLIAMS et al (1994)]
Figure 4a Leading edge channel heat transfer distribution with distance from the inlet. Comparison of model turbulated convex surface maximum, minimum and average measurement with blade CFD average predictions.
PRESSURE COEFFICIENTS AT THE CENTERLINE OF VEHICLE

NOTCHBACK 1 BODY STYLE

PRESSURE COEFFICIENTS AT THE CENTERLINE OF VEHICLE
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