Challenges in Evaluating Turbulence Models with Benchmark Cases

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Background

- Why is turbulence modeling important in the Personal Micro-Environment (PME)?
  - *Is almost always encountered in PME flows*
  - *Turbulence is often on the same order as the mean flow*
  - *Important for other assessments (thermal comfort, personal exposure)*

- Why is turbulence modeling difficult in the PME?
  - *Few canonical benchmark cases with high fidelity data of known error to validate models*
  - *Often involve one or several known problematic turbulent phenomena*
    i. Jet flows
    ii. Transitional Reynolds number flows
    iii. Thermal buoyancy

- Example: PME benchmark case
  - *Displacement ventilation with standing heated manikin*
Displacement Ventilation Set-up

- Standing thermal manikin in displacement type ventilation
- Flow now has a low-speed wall jet, thermal buoyancy and recirculating room flow

Standing Thermal Mannequin in Disp. Type Ventilation: side view

Standing Thermal Mannequin in Disp. Type Ventilation: front view
- Thermal plume of $v^2-f$ much thicker than standard $k-\varepsilon$
- Data as well LES confirmed that $v^2-f$ better predicts thermal plume
Large Eddy Simulation – Thermal Plume

- Large Eddy Simulation (dynamic Smagorinsky-Lilly)
  - ~7 million cells
  - $\Delta t = 1/5000$ sec. (min. cell length / max. velocity)
  - 180 sec. (flow-time) then saved 20 sec. (flow-time) data

Animation: LES (1), LES (2)
Experimental Data – Thermal Plume

- PIV measurements near the manikin
- $v^2-f$ predicts shape of thermal boundary layer much better than standard $k-\varepsilon$
- Spike in data horizontal velocity at face

Vertical Velocity: CFD – $v^2-f$, CFD – ske, Kato PIV data

Horizontal Velocity: CFD – $v^2-f$, CFD – ske, Kato PIV data
Displacement Ventilation – Inlet Jet

- Ultra-sonic anemometer measurements
- Experimental data shows rapid decay of CL jet velocity
- Predictions show CL jet velocity decreases slower

Normalized Centerline Velocity along Floor

Velocity Magnitude: CFD – $v^2$-f, CFD – ske, Kato U-S Anen, data
Axi-Symmetric Free Jet

- Looked at two fundamental jet problems to evaluate turbulence models
  - Axi-symmetric free jet
  - 3D wall jet (unconfined)
- RANS models can predict the important features of the axi-symmetric free jet:
  - Spread rate
  - Centerline velocity decay

<table>
<thead>
<tr>
<th></th>
<th>Experiment</th>
<th>Standard k-ε</th>
<th>v²-f</th>
<th>RSM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spread rate</td>
<td>0.10</td>
<td>0.123</td>
<td>0.090</td>
<td>0.113</td>
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<tr>
<td>B</td>
<td>6.0</td>
<td>4.93</td>
<td>6.33</td>
<td>5.18</td>
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3D Wall Jet

- Eddy-viscosity RANS models have difficulty predicting the 3D wall jet
- Experiments show lateral spreading rate 5-6x higher than normal
- Due to creation of streamwise vorticity from imbalance of fluctuating normal Reynolds stresses (*Kraft and Launder JFM 2001*)

### Table

<table>
<thead>
<tr>
<th></th>
<th>Exp.</th>
<th>Standard $k-\epsilon$</th>
<th>$\nu^2-f$</th>
<th>RSM</th>
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</thead>
<tbody>
<tr>
<td>Normal</td>
<td></td>
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<tr>
<td>$\frac{dy_{1/2}}{dz}$</td>
<td>0.065</td>
<td>0.089</td>
<td>0.078</td>
<td>0.050</td>
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<td>Lateral</td>
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<tr>
<td>$\frac{dx_{1/2}}{dz}$</td>
<td>0.320</td>
<td>0.085</td>
<td>0.076</td>
<td>0.646</td>
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<tr>
<td>Ratio</td>
<td>4.92</td>
<td>0.96</td>
<td>0.96</td>
<td>12.92</td>
</tr>
</tbody>
</table>

*3D Unconfined Wall Jet Schematic: figure from Kraft & Launder JFM 2001*
Confined 3D Wall Jet

- 3D jet from inlet confined by walls – spread and decay rates affected by walls
- Investigated this affect by using same displacement room without manikin

Inlet Non-Uniformity

- Inlet not uniform and average magnitude less than assumed
- Including non-uniformity did not improve prediction – normalized profiles nearly the same

\[ \bar{U}_{\text{inlet}} = 0.181 \text{ m/s}, \quad \text{std. dev.} = 0.0275 \text{ m/s} \]

Velocity Magnitudes Measured at Inlet

Normalized Centerline Velocity along Floor

Normalized Velocity Magnitude: CFD – RSM, Kato U-S Anen, Data ○
Inlet Velocity Angle

- Magnitude was measured at the inlet but no components
- RSM could not account for low centerline velocities of data
- Varying the direction of inlet velocity angle could account for difference

Normalized Centerline Velocity along Floor

Normalized Velocity Magnitude: CFD – ske, CFD – RSM
Summary & Questions

- $v^2-f$ predicts thermal plume better than the standard k-ε
- $v^2-f$ and standard $k-\varepsilon$ OK for axi-sym. jet but not for 3D wall jet – need full Reynolds stress
- RSM can not explain the trend in the centerline velocity data
- What is the interaction between the inlet jet and the thermal plume?
- Reliable measurement of mean and turbulence flow quantities – with known error estimates - needed for validation of PME flows
Acknowledgments

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