Heat transfer Predictions using Scale Resolving Simulation Turbulence Models

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Motivation for Scale-Resolving Simulations (SRS)

• Accuracy Improvements over RANS
  – Reduce uncertainty in CFD simulations relative to RANS
  – Flows with large separation zones (stalled airfoils/wings, flow past buildings, flows with swirl instabilities, etc.)

• Additional information required
  – Acoustics - Information on acoustic spectrum not reliable from RANS
  – Vortex cavitation – low pressure inside vortex causes cavitation – resolution of vortex required
  – Fluid-Structure Interaction (FSI) – unsteady forces determine frequency response of solid.
Turbulence Models

- **RANS Models**
  - 1-eq.,
  - 2-eq,
  - RSM,
  - EARSM
  - Transition
  - ...

- **LES Models**
  - Smagorinsky (reg., dyn)
  - WALE
  - k-equation (dyn.)
  - WMLES

- **Hybrid Models**
  - SAS
    - All $\omega$-equation based models
  - DES/DDES/IDDES
    - SA-based
    - SST-based
    - k-$\varepsilon$ based

**Zonal/Embedded Models**
Scale-Adaptive Simulation (SAS) 2-Equation Model

\[
\frac{\partial (k)}{\partial t} + \frac{\partial (U_j k)}{\partial x_j} = P_k - c_{\mu}^{3/4} \frac{k^{3/2}}{L} + \frac{\partial}{\partial x_j} \left( \frac{\nu_t}{\sigma_k} \frac{\partial k}{\partial x_j} \right)
\]

\[
\frac{\partial \Phi}{\partial t} + \frac{\partial (U_j \Phi)}{\partial x_j} = \frac{\Phi}{k} \left( \zeta_1 P_k - \zeta_2 \frac{1}{k^2} \nu_t \left( U'' \right)^2 \right) - \zeta_3 k + \frac{\partial}{\partial y} \left[ \frac{\nu_t}{\sigma_\Phi} \frac{\partial \Phi}{\partial y} \right]
\]

- With:

\[\Phi = \sqrt{kL} \quad \nu_t = c_{\mu}^{1/4} \Phi\]

\[|U'| = \sqrt{\frac{\partial U_i}{\partial x_j} \frac{\partial U_i}{\partial x_j}}; \quad |U''| = \sqrt{\frac{\partial^2 U_i}{\partial x_j \partial x_j} \frac{\partial^2 U_i}{\partial x_k \partial x_k}}; \quad L_{vK} = \kappa \left| U'' \right|
\]

v. Karman length-scale as natural length-scale:

\[L \sim \kappa \left| \frac{\partial U}{\partial y} \right| = L_{vK}\]
Detached Eddy Simulation (DES) for SST – Strelets (2000)

- **k-equation RANS**
  \[
  \frac{\partial (\rho k)}{\partial t} + \frac{\partial (\rho \bar{U}_j k)}{\partial x_j} = P_k - \rho \frac{k^{3/2}}{L_t} + \frac{\partial}{\partial x_j} \left[ (\mu + \frac{\mu_t}{\tilde{\sigma}_k}) \frac{\partial k}{\partial x_j} \right]
  \]

- **k-equation LES**
  \[
  \frac{\partial (\rho k)}{\partial t} + \frac{\partial (\rho \bar{U}_j k)}{\partial x_j} = P_k - \rho \frac{k^{3/2}}{C_{DES} \Delta} + \frac{\partial}{\partial x_j} \left[ (\mu + \frac{\mu_t}{\tilde{\sigma}_k}) \frac{\partial k}{\partial x_j} \right]
  \]

- **k-equation DES**
  \[
  \frac{\partial (\rho k)}{\partial t} + \frac{\partial (\rho \bar{U}_j k)}{\partial x_j} = P_k - \rho \frac{k^{3/2}}{\min \left( L_t; C_{DES} \Delta \right)} + \frac{\partial}{\partial x_j} \left[ (\mu + \frac{\mu_t}{\tilde{\sigma}_k}) \frac{\partial k}{\partial x_j} \right]
  \]

**Diagram:**
- **RANS**
  \[ L_t \leq c\Delta \]
- **LES**
  \[ L_t \geq c\Delta \]
LES Models: Summary

Sub-grid stress: turbulent viscosity

- Smagorinsky model ([Smagorinsky, 1963])
  - Need ad-hoc near wall damping

- WALE model ([Nicoud & Ducros 1999])
  - Correct asymptotic near wall behaviour

- Dynamic model ([Germano et al., 1991])
  - Local adaptation of the Smagorinsky constant

- Dynamic sub-grid kinetic energy transport model ([Kim & Menon 2001]) (Fluent only)
  - Robust constant calculation procedure
  - Physical limitation of backscatter

\[ \tau_{ij} - \frac{1}{3} \tau_{kk} \delta_{ij} = -2 \rho v_t \bar{S}_{ij} \]

\[ v_t = (C_s \bar{\Delta})^2 |\bar{S}| \]

\[ v_t = (C_s \bar{\Delta})^2 \left( \frac{S_{ij}^d S_{ij}^d}{(\bar{S}_{ij} \bar{S}_{ij})^{5/2} + (S_{ij}^d S_{ij}^d)^{5/4}} \right) \]

\[ v_t = (C_D \bar{\Delta})^2 |\bar{S}| \]

\[ v_t = C_k k_{sgs}^{1/2} \bar{\Delta} \]

\[ \frac{\partial k_{sgs}}{\partial t} + \frac{\partial \bar{u}_j k_{sgs}}{\partial x_j} = -\tau_{ij} \frac{\partial \bar{u}_i}{\partial x_j} - C_s k_{sgs}^{3/2} \bar{\Delta} + \frac{\partial}{\partial x_j} \left( \frac{\nu_{sgs}}{\sigma_k} \frac{\partial k_{sgs}}{\partial x_j} \right) \]
Unstructured Hex Mesh NACA 0012

- Re=10^6
- Span: 0.05 chord; 80 nodes
- In total ~ 11.4 Mio nodes
- WALE LES model
- Periodicity in spanwise direction
• Due to high Re number and moderate a, it looks still ok near trailing edge even though span=0.05c
5\%\text{chord}, 11\text{M} \text{cells}, \Delta t=1.5 \ \mu s

Pressure and skin friction coefficients

Even on this grid $c_f$ is too low $\rightarrow$ WMLES (see later)
WMLES: Near Wall Scaling

- Turbulent length scale is independent of Re number
- However thickness of viscous sub layer decreases with increasing Re number
- Turbulent structures inside sublayer are damped out
- Smaller turbulence structures near the wall get “exposed” as Re increases
- WMLES: models small near wall structures with RANS and only resolve larger structures – less dependent on Re number
- Some Re number dependence for boundary layer remains as boundary layer thickness decreases with Re number

\[
L_t = \kappa y
\]

\[
\nu_t = f_d \min \left\{ \left( \kappa d_W \right)^2, \left( C_{SMAG} \Delta \right)^2 \right\} S
\]
**WMLES – Channel Flow Tests**

<table>
<thead>
<tr>
<th>$Re_\tau$</th>
<th>Cells Number</th>
<th>LES Cells Number</th>
<th>Nodes Number</th>
<th>$\Delta X^+$</th>
<th>$\Delta Z^+$</th>
</tr>
</thead>
<tbody>
<tr>
<td>395</td>
<td>384 000</td>
<td>384 000</td>
<td>81×81×61</td>
<td>40.0</td>
<td>20.0</td>
</tr>
<tr>
<td>760</td>
<td>480 000</td>
<td>1 500 000</td>
<td>81×101×61</td>
<td>76.9</td>
<td>38.5</td>
</tr>
<tr>
<td>1100</td>
<td>480 000</td>
<td>4 000 000</td>
<td>81×101×61</td>
<td>111.4</td>
<td>55.7</td>
</tr>
<tr>
<td>2400</td>
<td>528 000</td>
<td>19 000 000</td>
<td>81×111×61</td>
<td>243.0</td>
<td>121.5</td>
</tr>
<tr>
<td>18000</td>
<td>624 000</td>
<td>1 294 676 760</td>
<td>81×131×61</td>
<td>1822.7</td>
<td>911.4</td>
</tr>
</tbody>
</table>

- **Very large savings between WMLES and wall-resolved LES**
- **Alternative is LES with wall functions – however $\Delta x^+$ and $\Delta z^+$ are a function of $\Delta y^+$**
Embedded/Zonal Large Eddy Simulation (ELES)

- Suitable if zone with high accuracy demands is embedded into larger domain which can be covered properly by RANS models.
- Limited zone can then be covered by LES or Wall-Modelled WMLES model.
- LES zone needs to be coupled to RANS zone through interfaces.
- LES zone requires suitable (WM)LES resolution in time and space.
Zonal LES: Test cases

DIT-x: decay rate validation

- Modelled and resolved $k$

![Kinetic energy of turbulence graph](image.png)

- $k$ modelled
- $k$ resolved
- $k$ modelled, pure RANS
Vortex Method

- In essence, vorticity-transport is modeled by distributing and tracking many point-vortices on a plane (Sergent, Bertoglio, Laurence, 2000)

\[
\omega(x, t) = \sum_{k=1}^{N} \Gamma_k(t) \eta(|x - x_k|, t)
\]

- Velocity field computed using the Biot-Savart’s law

\[
u(x, t) = -\frac{1}{2\pi} \int\int \frac{(x - x') \times \omega(x') e_z}{|x - x'|^2} d\mathbf{x'}
\]
Harmonic Turbulence Generator (HTG)

- Input from turbulence model in form of $L_t$ and $\omega$.
- Produces Karman spectrum
- Co-operation with Profs. Strelets and Shur (St. Petersburg)

$$\tilde{u}_i = 2 \sum_{n=1}^{N} \hat{u}_{(n)} \cos \left( \kappa_{(n),j} \cdot x_j + \hat{\omega} t + \psi_{(n)} \right) \tilde{\sigma}_{(n),i}$$

$$k_{HTG} = (k_{RANS} - k_{LES})$$

$$\sum_{n=1}^{N} \hat{u}_{n}^2 = k_{RANS} - k_{LES}$$

$$\kappa \sim \frac{1}{L_t}, \quad \hat{\omega} \sim \omega, \quad L_t = \frac{\sqrt{k}}{c_\mu \omega}$$
WMLES – Boundary Layer

- Boundary layer simulation:
  - WMLES
  - Inlet: synthetic turbulence
    Vortex Method
  - 2 different Reynolds numbers

- Skin Friction Coefficient

- Reθ=1000

- Reθ=10000
Flow Types: Globally Unstable Flows

- Types of highly unstable flows:
  - Flows with strong swirl instabilities
  - Bluff body flows, jet in crossflow
  - Massively separated flows

- Physics
  - Resolved turbulence is generated quickly by flow instability
  - Resolved turbulence is not dependent on details of turbulence in upstream RANS region (the RANS model can determine the separation point but from there ‘new’ turbulence is generated)

- Models
  - **SAS:** Most easy to use as it converts quickly into LES mode, and automatically covers the boundary layers in RANS. Has RANS fallback solution in regions not resolved by LES standards ($\Delta t, \Delta x$)
  - **DDES:** Similar to SAS, but requires LES resolution for all free shear flows ($\Delta t, \Delta x$) (jets etc.)
  - **ELES:** Not really required as RANS model can cover boundary layers. Often difficult to place interfaces for synthetic turbulence.

Green-recommended,  Red=not recommended
Flow Types: Locally Unstable Flows

- **Types of moderately unstable flows:**
  - Jet flows, Mixing layers ...

- **Physics**
  - Flow instability is weak – RANS/SAS models stay steady state.
  - Can typically be covered with reasonable accuracy by RANS models.
  - DDES and LES models go unsteady due to the low eddy-viscosity provided by the models. Only works on fine LES quality grids and time steps. Otherwise undefined behavior.

- **Models**
  - **SAS:** Stays in RANS mode. Covers upstream boundary layers in RANS mode. Can be triggered into SRS mode by RANS-LES interface.
  - **DDES:** Can be triggered to go into LES mode by fine grid and small $\Delta t$. Careful grid generation required. Covers upstream boundary layers in RANS mode.
  - **ELES:** LES mode on fine grid and small $\Delta t$. Careful grid generation required. Upstream boundary layer (pipe flow) in expensive LES mode. Alternative – ELES with synthetic turbulence RANS-LES interface.

Green-recommended, Red=not recommended
Flow Types: Stable Flows

- **Types of marginally unstable flows:**
  - Pipe flows, channel flows, boundary layers, ..

- **Physics**
  - Transition process is slow and takes several boundary layer thicknesses.
  - When switching from upstream RANS to SRS model, RANS-LES interface with synthetic turbulence generation required.
  - RANS-LES interface needs to be placed in non-critical (equilibrium) flow portion. Downstream of interface, full LES resolution required.

- **Models**
  - **SAS**: Stays in RANS mode. Typically good solution with RANS. Can be triggered into SRS mode by RANS-LES interface.
  - **DDES**: Can be triggered to go into LES mode by fine grid and small $\Delta t$. Careful grid generation required. Covers upstream boundary layers in RANS mode.
  - **ELES**: LES mode on fine grid and small $\Delta t$. Careful grid generation required. Upstream boundary layer (pipe flow) in RANS mode. Synthetic turbulence RANS-LES interface.

Green-recommended, Red=not recommended
Validation of RANS Models

• A comparison between the SST solution and the experimental data for different \( \text{Re}_X \) shows that:
  - SST model almost perfectly predicts the temperature profiles for \( \text{Pr}=0.7 \)
  - The difference between the SST model and the experimental results is less than 10%

• Hence SST model can be used as a reference solution
Validation: Backward Facing Step

- Virtually the same skin friction distributions are obtained downstream of the step on baseline and uniform 20x20 grids.
- Grid coarsening leads to “improvement” due to error cancellation.
- WALE and IDDES models are virtually identical within the separation zone.
- Grid is sufficient for LES calculations.
- The difference between WALE and IDDES models upstream and downstream of the separation zone is due to insufficient grid resolution in these regions.
Validation: Backward Facing Step

- Similar to the BL flow there is a strong influence of the grid on the Stanton number
  - Grid coarsening in wall normal direction leads to substantial deterioration of the results
- The Stanton number distribution for the WALE model is about 10% lower than those of IDDES for all the considered grids
  - This results are consistent with previous observation for the BL flow
Globally Unstable Flow – Jets in Crossflow

PhD project Benjamin Duda
- 18 month at Airbus Toulouse (Marie-Josephe Estève)
- 18 month ANSYS Germany (Thorsten Hansen, F. Menter)
- Scientific supervisors: Herve Bezard, Sebastien Deck

Problem:
- Hot air leaves engine nacelle and heats wall
- Heat shielding required
- Experiments too expensive
- RANS not accurate enough
- Simulations ANSYS-Fluent

Courtesy: Benjamin Duda, Airbus Toulouse
Generic Jet in Cross Flow Configuration

- Infrared Thermography
- Particle Image Velocimetry
- Laser Doppler Anemometry
- Hot and Cold Wire Measurements

Courtesy: Benjamin Duda, Airbus Toulouse
Hexahedral Mesh

- 12,900,000 Elements
- Min angle = 28.1°
- Max AR = 3,500
- Max VC = 10

Courtesy: Benjamin Duda, Airbus Toulouse
Hybrid Tetrahedral Mesh

21,000,000 Elements
Min angle = 20.0°
Max AR = 7,600
Max VC = 8

20 inflation layers

Courtesy: Benjamin Duda, Airbus Toulouse
Hybrid Cartesian Mesh

13,100,000 Elements
Min angle = 6.0°
→ 30 Elements < 15°
Max AR = 6,000
Max VC = 16

20 inflation layers

Courtesy: Benjamin Duda, Airbus Toulouse
Validation Matrix

Hex | 2Δt |
---|-----|
SAS |     |

Cart | Δt |
---|----|
SAS |     |

Tet | Δt |
---|----|
SAS |     |

Hex | Δt |
---|----|
SAS |     |

Hex | Δt |
---|----|
DDES |     |

Hex | Δt |
---|----|
ELES |     |

Hex | Δt |
---|----|
URANS |     |

Hex | 0.5Δt |
---|-------|
SAS |      |

Time step

Mesh

Turbulence model

Courtesy: Benjamin Duda, Airbus Toulouse
Scale Resolvability of Turbulence Models

$Q$-criterion:

SAS | DDES
---|---
ELES | URANS

Courtesy: Benjamin Duda, Airbus Toulouse
Mean X-Velocity

![Graph showing Mean X-Velocity with various curves for EXP, SAS M1, SAS M2, and URANS. The graph includes a section labeled "URANS SAS M2" and "SAS M1." The data is courtesy of Benjamin Duda, Airbus Toulouse.]
Mean X-Velocity

- Embedded LES (ELES) is more consistent at the first station, as expected.
Time Averaged Temperature Distribution II

Turbulence models (on hex)
- Lateral spreading of temperature in good agreement with all three SRS
- Poor URANS prediction due to unphysical damping of lateral jet wake movement

Meshing strategies (with SAS)
- Generally very good agreement
- Small underestimation for hex mesh at center

\[ \eta = \frac{\bar{T} - T_\infty}{T_j - T_\infty} \]

Courtesy: Benjamin Duda, Airbus Toulouse
Mean Thermal Efficiency on Wing Surface

\[ \bar{\eta} \]

\begin{array}{c}
0.80 \\
0.75 \\
0.70 \\
0.65 \\
0.60 \\
0.55 \\
0.50 \\
0.45 \\
0.40 \\
0.35 \\
0.30 \\
0.25 \\
0.20 \\
0.15 \\
0.10 \\
0.05 \\
0.00 \\
\end{array}

URANS

SAS

EXP

Courtesy: Benjamin Duda, Airbus Toulouse
Heat Conduction in Ejector Grid

- Take into account heat conduction through solid
- Material: stainless steel
- Approach:
  - Run steady state computation with heat transfer
  - Use surface temperature distribution as thermal boundary condition for transient calculation
- No increase of computational costs for transient runs

Courtesy: Benjamin Duda, Airbus Toulouse
Mean Thermal Efficiency on Wing Surface

\[ \eta \]

SAS, M2

EXP

Courtesy: Benjamin Duda, Airbus Toulouse
RMS of X-Velocity on Symmetry Plane

\[ \sqrt{u'^2} \]

\[ \frac{\sqrt{u'^2}}{U} \]

SAS

EXP

Courtesy: Benjamin Duda, Airbus Toulouse
Hot Jet in Crossflow: Conclusions

- RANS models are not able to reliably predict such flows and are therefore not useful as design tools.
- A systematic study was carried out to evaluate SRS models for such applications.
- In this study (for several test case configurations) it was found that all SRS methods worked equally well in predicting the main flow characteristics.
- On suitable grids (~$10^6$ cells) good agreement even in the secondary quantities (stresses) could be achieved.
- More complex geometries studied.
Water of different temperature is mixing in the T-junction at $\text{Re}=1.4 \cdot 10^5$ (based on the main pipe bulk velocity and on its diameter).

**Main Pipe:**
- $T=19^\circ$
- $Q=9 \text{ [l/s]}$
- $\varnothing=0.14 \text{ [m]}$

**Branch Pipe:**
- $T=36^\circ$
- $Q=6 \text{ [l/s]}$
- $\varnothing=0.1 \text{ [m]}$
- $\delta_{BL}=0.01 \text{ [m]}$

The target values are mean and RMS wall temperatures in the fatigue zone.
Isosurfaces of Q-criterion Colored with Temperature for Different SRS Models

- Sensitivity to numerics depends on the SRS model
- SAS with BCD is virtually steady
- The reason is that the flow is not enough unstable
- Unsteady solution with resolved turbulent structures is obtained for the CD scheme
- For other models the effect of numerics is not seen from instantaneous fields
Comparison of Different SRS Models

- CD scheme is used for comparison between different SRS models
- All models are able to predict mean and RMS profiles with sufficient accuracy
Influence of Zonal LES, weak BCD

Wall temperature in the fatigue zone

- Noticeable differences appear when looking at the wall temperature.
- All global models failed to provide the correct temperature distribution right past the intersection.
- Only zonal (embedded) formulation is able to provide the correct mixing already from the start of the mixing zone.

\[
\bar{\theta} = \frac{\overline{T} - T_{\text{cold}}}{T_{\text{hot}} - T_{\text{cold}}}, \quad \text{top wall line}
\]
Influence of Zonal LES, weak BCD

With DDES, $Q=1000$

View from the top

Different mixing pattern

With zonal LES, $Q=8000$
Overall Summary

- SRS is making its way into industrial CFD
- Heat Transfer Simulations are a key application area for SRS
  - High accuracy requirements
  - Limited accuracy of RANS models
- Currently favored methods within ANSYS software:
  - SAS – globally unstable flows
  - DDES – globally and locally unstable flows
  - ELES/WMLES stable flows
- Ongoing work:
  - Synthetic turbulence is good – but far from perfect
  - WMLES requires special grid resolution – not as generic as other models (inherited from LES)
  - Improved wall treatment for heat transfer predictions
  - User guidelines