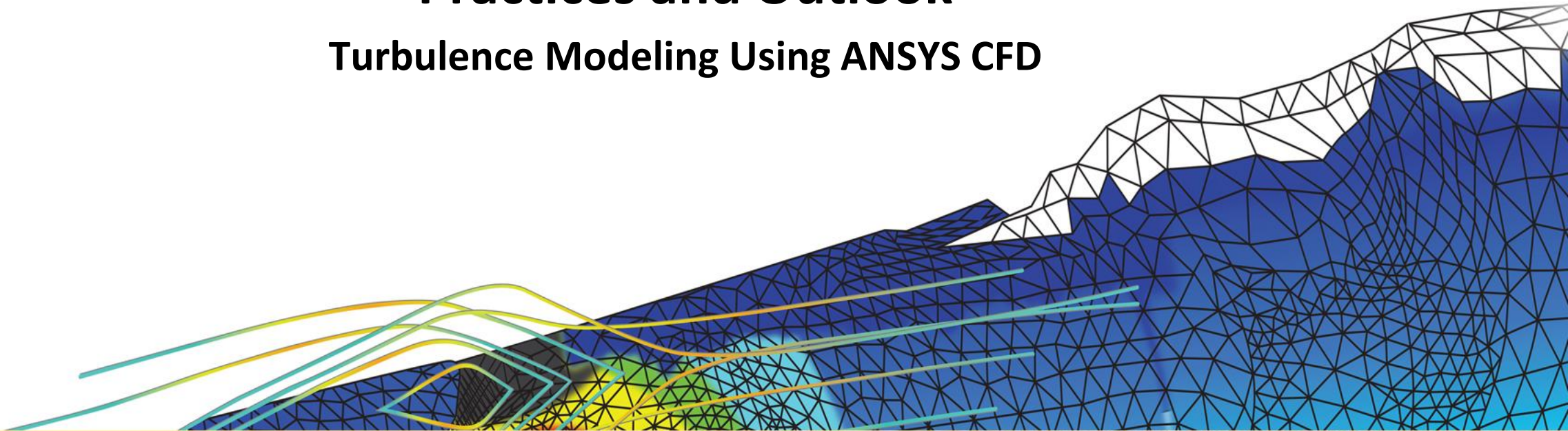




Lecture 09: Turbulence Modelling Best Practices and Outlook

Turbulence Modeling Using ANSYS CFD

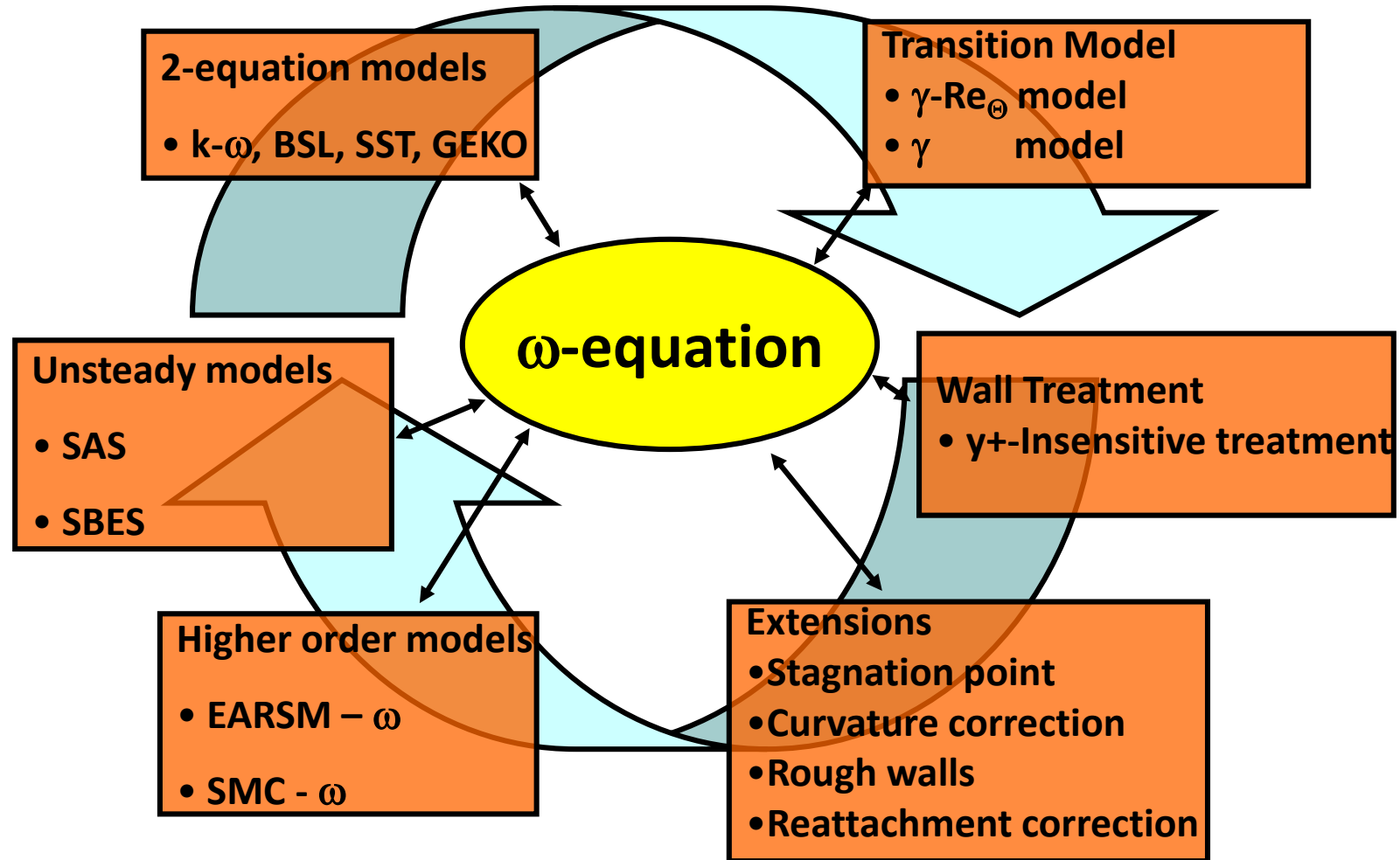


RANS Turbulence Models: Which to select?

- Many RANS models and model variants in both codes ANSYS Fluent and ANSYS CFX are a result of historic developments
- ANSYS recommends models from within the $k-\omega$ family for the following reasons:
 - Most accurate and robust formulation
 - Most simple and optimal wall treatment (y^+ -insensitive)
 - Highest compatibility with all other options on the codes – especially laminar-turbulent transition models
 - Highest flexibility
 - Re-tuning of a_1 coefficient in SST models
 - Tuning of GEKO model over a wide range of flow conditions
- All current models (e.g. $k-\epsilon$, etc.) in the codes will be supported in the future, but with limited advancement
- Existing $k-\epsilon$ models can be transformed to GEKO model

Reminder: Integration Platform ω -equation

- Turbulence Modeling requires a basic scale equation
- In ANSYS CFD the ω -equation serves that purpose
- Recommended models families
 - SST/BSL
 - GEKO
 - RSM- ω
- Use extensions as required



Choices within the k- ω Model Family

- **Eddy-Viscosity Models:**
 - SST
 - Good starting point
 - Fairly accurate separation prediction overall
 - Can be tuned from boundary layer separation sensitivity with parameter a_1 (increasing a_1 will delay separation)
 - Values $a_1 > 0.4$ are essentially like BSL model
 - Model is fully published
 - GEKO
 - Offers a wide range of calibration coefficients which can be tuned globally or locally
 - Can mimic other models (like SST, or k- ϵ , ...)
 - Currently unpublished

Choices within the k- ω Model Family (continued)

- **EARSM/RSM**
 - **EARSM-WJ (β in Fluent)**
 - In combination with BSL or GEKO (tuneable)
 - Potential improvements:
 - Corner flow separation
 - No benefit for swirl or curvature without additional curvature correction
 - **RSM**
 - Use in combination with BSL
 - Potential improvements:
 - Corner flow separation
 - Swirl or curvature included
 - Complex interactions of different flow features (potentially better than Eddy-viscosity)
 - However – often robustness problems

Questions to Ask Before Simulation

- **Is the flow composed of sub-flows for which RANS models are suitable?**
 - If yes, select optimal RANS model
 - If not, can I tune the GEKO model to match the flow?
 - If not, use Scale-Resolving Simulation – mostly hybrid models like SBES (consider costs)
- **What is my Reynolds number?**
 - In case of moderate Re numbers (10^4 - 10^6) and boundary layers do I need to include laminar-turbulent transition?
- **Should I activate curvature correction?**
- **Do I need to consider additional physics?**
 - Buoyancy in case of density layering?
 - Wall roughness?
 - ...

Questions to Ask Before Simulation

- How much of the geometry do I need to include? How far away do I need to place my boundaries? Should I test the impact of such decisions (recommended)?
- What are the meshing requirements and the time-scale/cost of the simulation?
- Can I afford to perform a mesh refinement study – or has one of my colleagues done that before for a similar case? Mesh studies are recommended.
- How accurately do I know the boundary conditions? Do I need to perform a sensitivity study with variations in BCs?
- What are the optimal solver/numerics settings
 - For “steady” state simulations - be very cautious to accept non-converged solutions. Better to switch to “unsteady” settings
 - Especially important for unsteady SRS simulations – where optimal settings can save significant CPU/project time
 - For SRS – when do I start averaging and for how long?

Options within the k- ω Model Family

- **Options:**
 - **Wall Treatment**
 - No options – always optimal y^+ -insensitive
 - **Curvature correction**
 - Use for swirl/rotation dominated flows
 - **Laminar-turbulent Transition**
 - Use Intermittency Transition model
 - Simpler than Transition SST model and Galilean invariant
 - **Corner flows**
 - Use Stress-BSL or EARSM WJ
 - **Additional options**
 - Stagnation point
 - Pk limiter default (for GEKO also realizability constraint)
 - Kato-Launder – additionally activated for transition models

Options within the k- ω Model Family (continued)

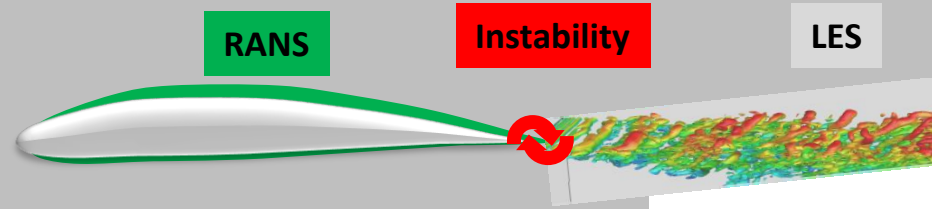
- **Options:**
 - **Wall roughness**
 - Select in case wall roughness larger than $h^+ \sim 5$
 - **Buoyancy**
 - As needed for stable or unstable stratified flows (temperature or density layered)
 - **Compressibility Effects:**
 - Affects flows for high Mach number ($Ma > 4$)
 - Calibrated for Mixing layer but not well tested for boundary layer flows
 - **Low-Re corrections (Fluent)** - do not use. It mimics transition but if the flow is transitional it is better to use one of the transition models

If SRS - Which Model?

- **For most technical flows the SBES model is optimal:**
 - Simple set-up
 - Automatic detection of RANS and LES zones
 - Quick ,RANS-LES Transition‘
 - Can be run in WMLES mode if triggered into SRS mode
 - By synthetic turbulence generator
 - By upstream separation-induced LES zone (e.g. backstep)
 - SBES is always superior compared to models of the DES family
- **The Scale-Adaptive Simulation (SAS) model**
 - Advantage - SAS has a URANS/RANS fall-back solution on coarse grids and time steps – this is sometimes beneficial
 - Disadvantage – SAS can stay in steady or URANS mode for flows with weak flow instabilities

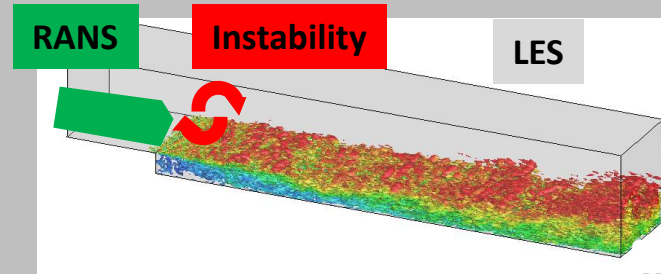
Global Hybrid RANS-LES Model Scenarios

- **Flow detaches at corner**
 - Boundary layer in RANS mode
 - Free shear layers in LES



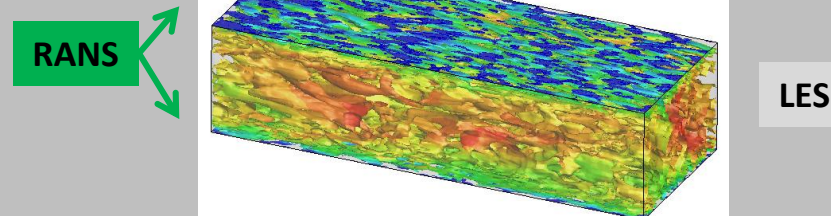
Classical Use of Hybrids

- **Flow Separates and reattaches**
 - Flow should remain in LES downstream of step
 - Recover to RANS on coarse grids downstream



Advanced Use of Hybrid

- **Flow is Wall bounded**
 - Should hybrid model do WMLES?

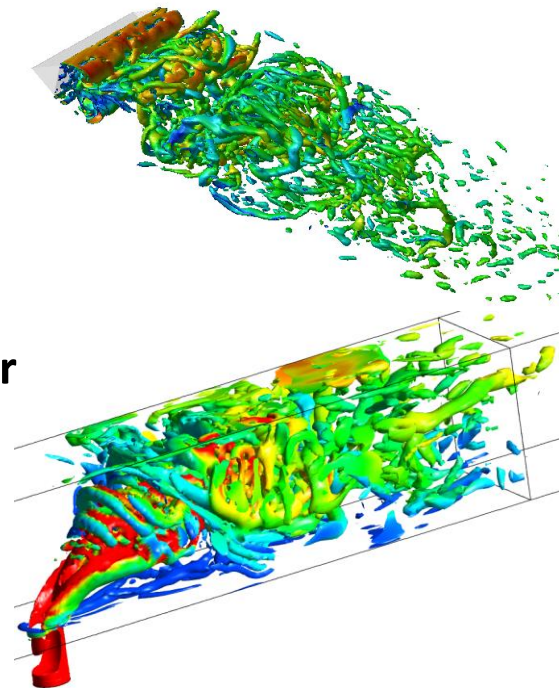
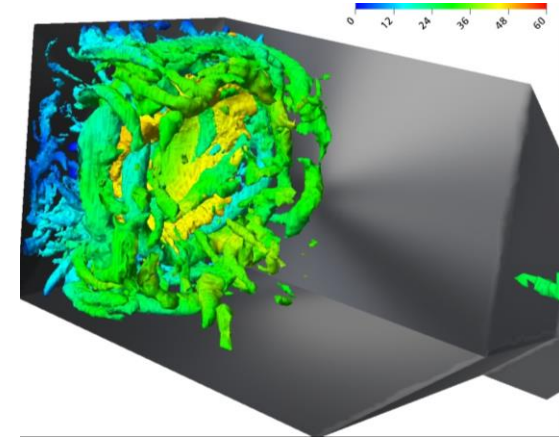


Ideally Hybrids should be able to work in WMLES

SRS Flow Types: Globally Unstable 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)
- Types of highly unstable flows:
 - Flows with strong swirl instabilities
 - Bluff body flows, jet in crossflow
 - Massively separated flows
- Models
 - For these flows basically all hybrid RANS-LES models work well
 - **SBES**: Most optimal global hybrid RANS-LES model, but requires LES resolution for all free shear flows (Δt , Δx) (jets etc.)
 - **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 (Δt , Δx). Might be better on coarse grids
 - **ELES**: Not really required as flow instability is strong enough to push the model into LES mode. Often difficult to place interfaces for synthetic turbulence.

Green=recommended,
Red=not recommended



Flow Types: Locally Unstable Flows

- Physics

- Flow instability is weak – RANS/SAS models stay steady state.
- Can typically be covered with reasonable accuracy by RANS models.
- SBES and DES 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.

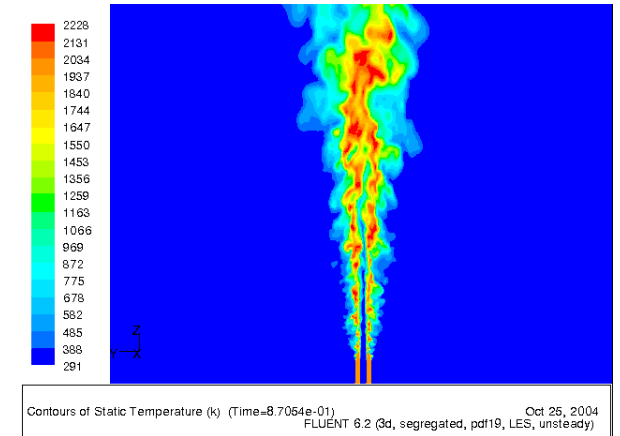
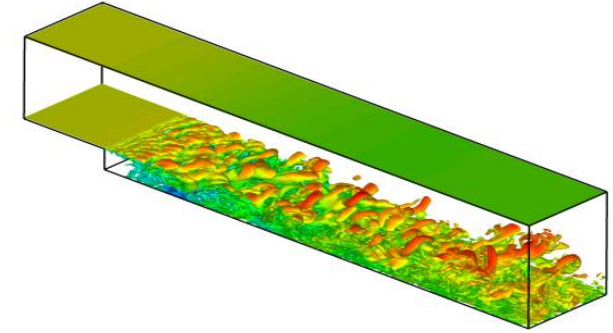
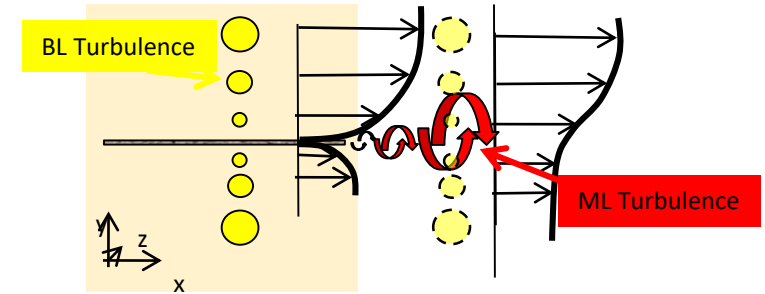
- Types of moderately unstable flows:

- Jet flows, Mixing layers ...

- Models

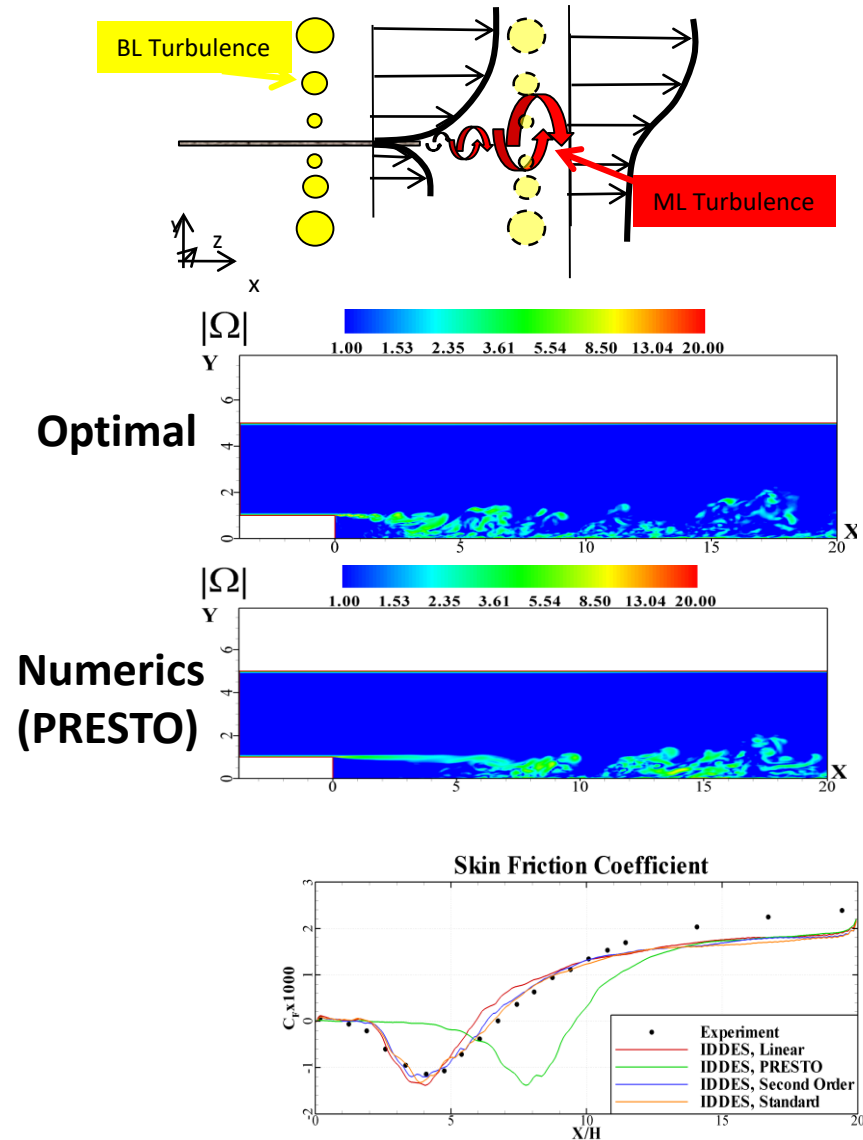
- **SAS**: Stays in RANS mode. Covers upstream boundary layers in RANS mode. Can be triggered into SRS mode by RANS-LES interface.
- **SBES**: Can be triggered to go into LES mode by fine grid and small Δt . Careful grid generation required. Covers upstream boundary layers in RANS mode.
- **ELES**: LES mode on fine grid and small Δt . Careful grid generation required. Upstream boundary layer (pipe flow) in expensive LES mode.

Green-recommended,
Red=not recommended



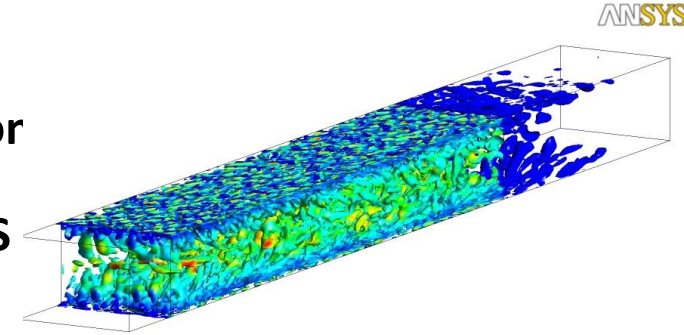
Flow Types: Locally Unstable Flows – Example Backstep

- Resolving flow instability in moderately unstable flows is demanding in terms of:
 - Grid resolution – needs to be of LES quality
 - Numerics – more demanding than fully turbulent LES
 - Difficult in complex industrial flows
- Backstep example shows strong sensitivity to details
 - Simulation run with IDDES model on marginal grid
 - Hard to start ,transition' from RANS to LES by flow instability
 - Fine mesh and optimal numerics required
 - However, SBES model produces lower eddy-viscosity than DDES in LES zone and reduces mesh/numerics sensitivity



Flow Types: Marginally Unstable Flows

- Types of marginally unstable flows:
 - Pipe flows, channel flows, boundary layers, ..
- Physics
 - ‘Transition’ process is slow and takes several boundary layer thicknesses if or switches only the turbulence model from RANS to LES at an interface.
 - Therefore when switching from upstream RANS to SRS model, a RANS to LES interface with synthetic turbulence generation required.
 - The 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 Δt . Careful grid generation required. Covers upstream boundary layers in RANS mode.
 - **SBES**: Can be triggered by synthetic turbulence into WMLES mode
 - **ELES**: LES mode on fine grid and small Δt . Careful grid generation required. Upstream boundary layer (pipe flow) in RANS mode. Synthetic turbulence RANS-LES interface.



Green=recommended,
Red=not recommended

Flow Types SRS: Summary

- In model selection and numerical set-up consider flow-type
- The application of hybrid SRS models is established for flows away from walls (free shear flows)
 - Wall boundary layers in RANS and free shear flows in LES mode
 - The SBES model is always superior to models of the DES family!
 - The SAS model should be used with only in case of strong flow instability and when time step and grid are too coarse for SBES (SAS recovers URANS on very large time steps)
- For Wall-Bounded Flows in SRS model (LES, WMLES)
 - In case LES/WMLES is required inside the boundary layer, the CPU costs are increasing dramatically
 - Be aware that LES/WMLES simulations are at the limit of engineering feasibility and that they require project resources (time and computing power) which are often not realistic
 - Only with very fine meshes and careful set-up will LES/WMLES for boundary layers be better than an optimized RANS model

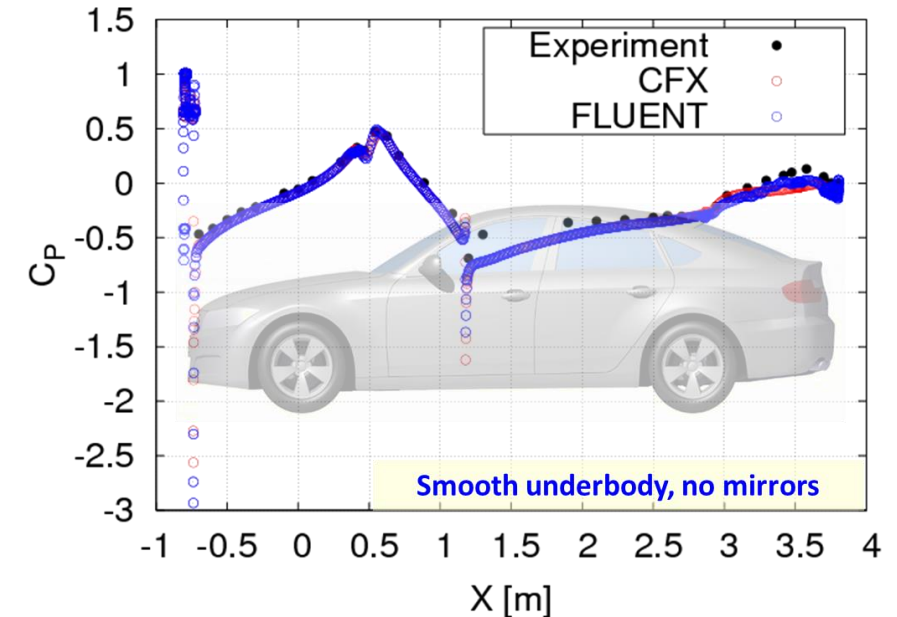
Aeronautical Flows

- For aeronautics flows the SST model is considered one of the most accurate models
 - Add Curvature Correction for tip vortex flows
 - Add laminar-turbulent transition model for ,untripped' flows
 - Use fine mesh in boundary layer ($y^+ \sim 1$ and > 20 prism layers)
 - Add EARSM in case of sharp corners
 - Activate ,Viscous Heating'
- Alternatives
 - GEKO model with SST-like settings
 - Spalart Allmaras Model



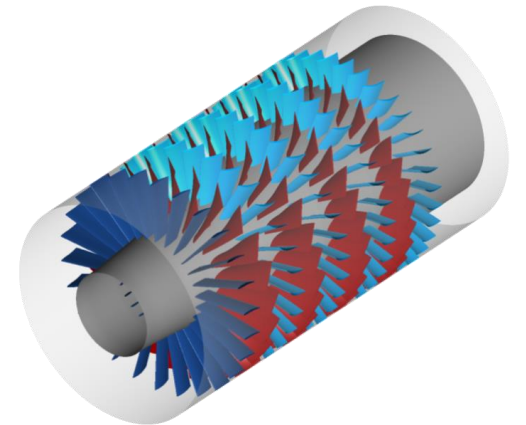
External Automotive Flows

- For automotive aerodynamics flows the SST model is considered too aggressive on separation which can lead to over-prediction of separation and unsteadiness
 - Increase a_1 coefficient ($a_1 \sim 0.35$) or use BSL model
 - Improved predictions can be obtained by Scale-Resolving Simulations (SRS) – use SBES model
 - Use 10-20 prism layers on aerodynamic surfaces
- Alternatives
 - GEKO model with BSL-like settings ($C_{SEP} \sim 1$)
 - GEKO-SBES in case unsteady turbulence (around wheels or behind the car) needs to be resolved



Turbomachinery Blade Flows

- **For turbomachinery blade flows the SST model is typically used with default settings**
 - Laminar turbulent transition modeling is often essential – use γ - Re_θ or γ one equation model
 - In case of transition simulations ensure good estimate of inlet turbulence levels
 - Use fine mesh for wall boundary layers, especially with transition models (20-30 prism layers)
 - In CFX use ,Blended Near Wall treatment‘
 - Use EARSM for hub-blade (hub-shroud) separation
 - Consider if ,Wall Roughness‘ option is required
- **Alternatives**
 - Use and tune GEKO model
 - BSL/GEKO EARSM

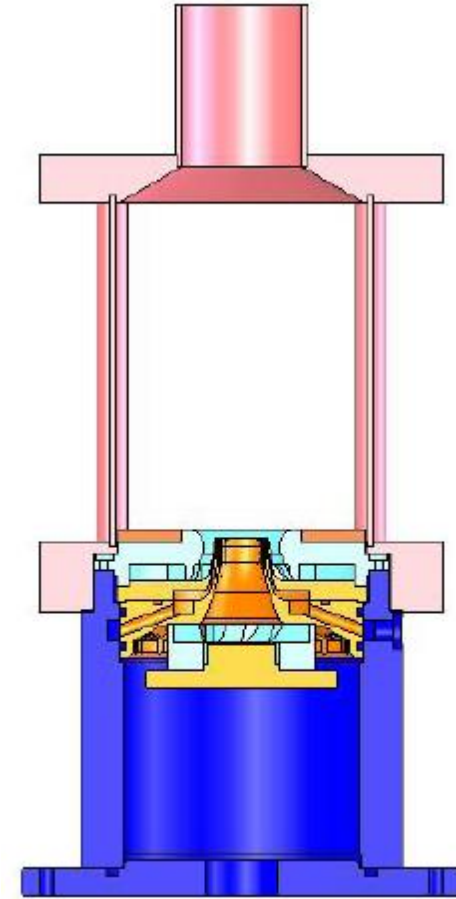


General Industrial Flows

- **General Industrial Flows are flows where separation is often fixed by the geometry (edges, corners)**
 - Use SST model – or BSL for reduced separation onset sensitivity
 - Many ,industrial‘ flows are not strongly guided by walls and feature large separation zones
 - RANS can lead to overly large separation zones and/or incorrect flow topology
 - Use Scale-Resolving Simulation (SRS) models (SBES or SAS) to predict correct large-scale mixing and interaction
 - For flows with strong swirl use
 - Reynolds Stress Models or add Curvature Correction
 - SBES to resolve vortices
- **Alternatives**
 - GEKO offers high flexibility to adjust the model coefficients to application
 - GEKO coefficients can even be tuned differently (UDF) in different regions

Combustion Chambers

- Combustion chambers are designed to create strong mixing
- Use SRS model to resolve turbulence in the mixing/combustion zones
- In case heat transfer is important, use global hybrid model – SBES to cover boundary layers in RANS mode

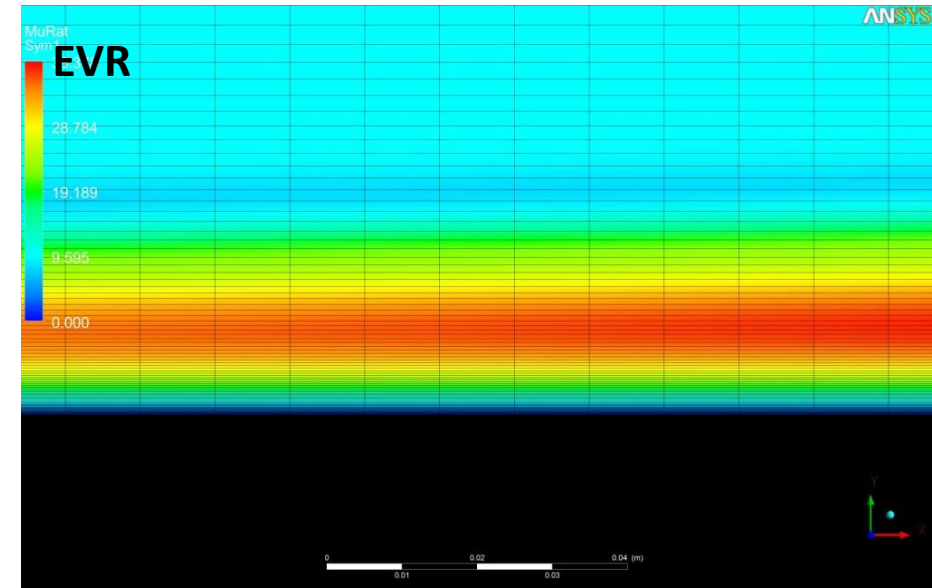


Courtesy DLR Stuttgart – Axel Widenhorn

Best Practice: Boundary Layer Resolution

- Boundary layers require a minimum resolution for accurate results
- Number of cells depends on accuracy requirements
- For aerodynamic flows, one should have more than 10 cells inside the boundary layer – for highly accurate simulation even up to $N_y \sim 30-40$.
- For industrial flows around $N_y \sim 10$ should be the target
- For complex flows, it is possible that one can only afford a few prism layers (3-5). In this case accuracy can be compromised
- Count prism layers inside boundary layer by plotting EVR with mesh on top (the mesh shown here is very fine)

Very fine mesh for transition prediction



$$EVR = \frac{\mu_t}{\mu}$$

EVR typically clearly indicates boundary layer as it has maximum in the middle of the layer

Best Practice: Mesh Requirements for Transition Modeling

- **Very fine meshes are required in the boundary layer normal to wall**
 - **Resolve the very thin laminar boundary layer**
 - **Resolve the transitional process**
 - **Resolve laminar-turbulent bubbles**
- **Mesher can be based on y^+ wall values and Expansion Rate (ER) of sequence of cells**

$$ER = \frac{\Delta y_{j+1}}{\Delta y_j}$$

- **Fine meshes in streamwise direction can be necessary to resolve laminar separation bubble with turbulent reattachment**

Best Practice Documents for GEKO and Scale-Resolving Simulations

- Two Best Practice Documents are provided with the course material
 - *Best Practice: Generalized $k-\omega$ Two-Equation Turbulence Model in ANSYS CFD (GEKO)*
 - *Best Practice: Scale-Resolving Simulations in ANSYS CFD*

