Scale-Resolving Simulations in Industrial CFD - Models and Best Practice

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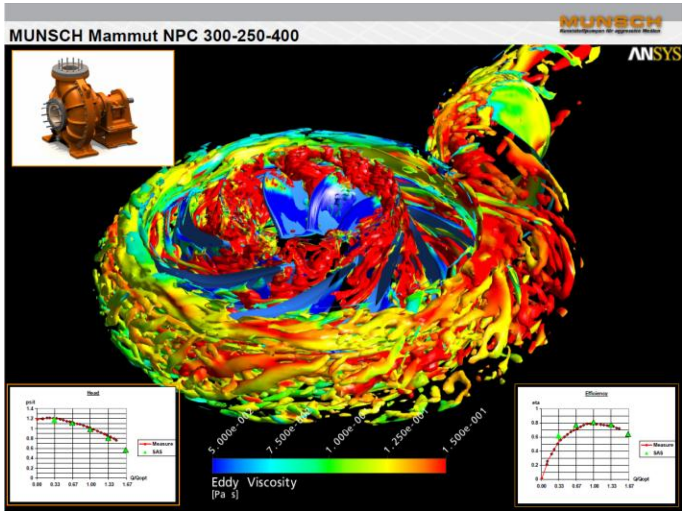
Motivation for Scale-Resolving Simulation (SRS)

- Accuracy Improvements over 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.



LES - Wall Bounded Flows

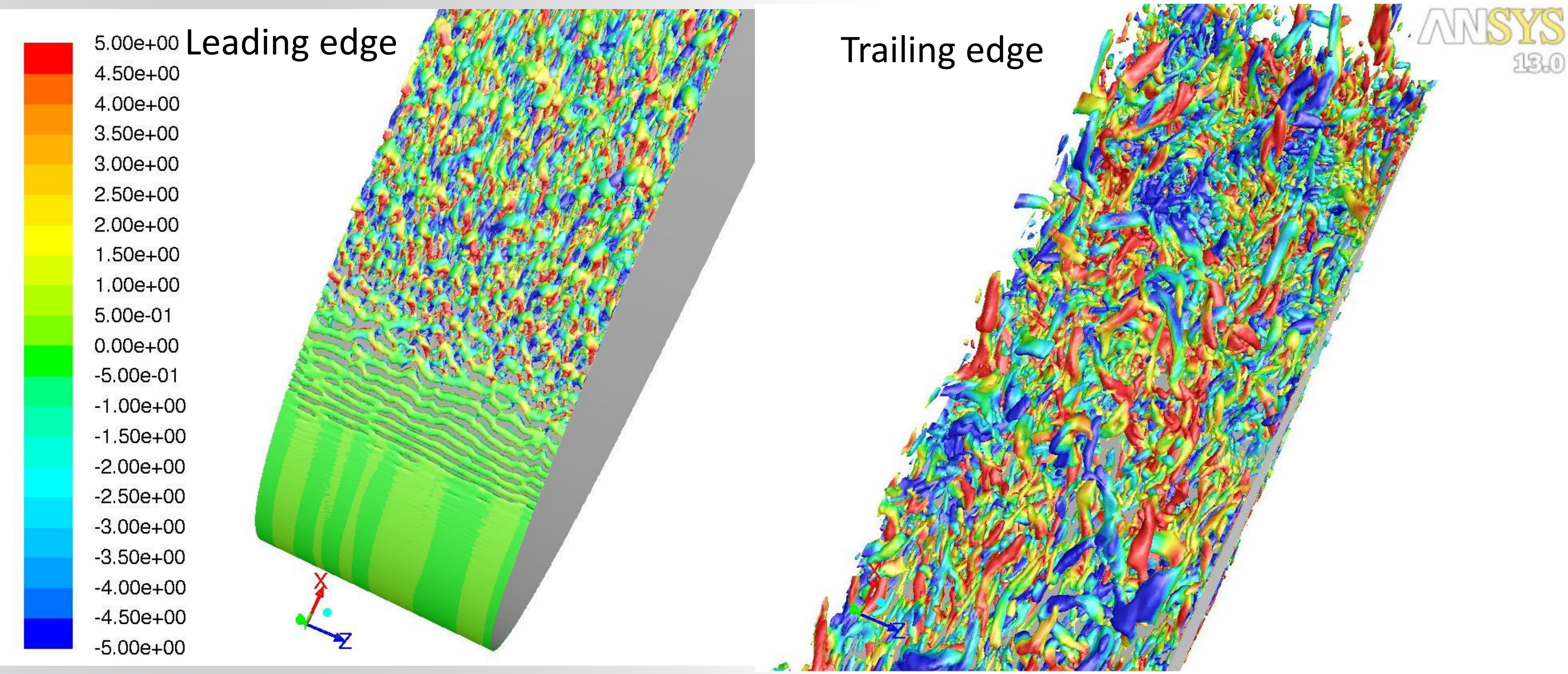
- A single Turbine (Compressor) Blade (Re=10^5-10^6) with hub and shroud section
- Need to resolve turbulence in boundary layers
- Need to resolve laminar-turbulent transition

Method	Number of Cells	Number of time steps	Inner loops per Δt.	CPU Ratio
RANS	~10^6	~10^2	1	1
LES	~10^8-10^9	~10^4-10^5	10	10^6

Therefore Hybrid RANS-LES Methods

Q-criterion

Q-criterion (Ω^2-S^2): Q=10^9 , colored by z-velocity:



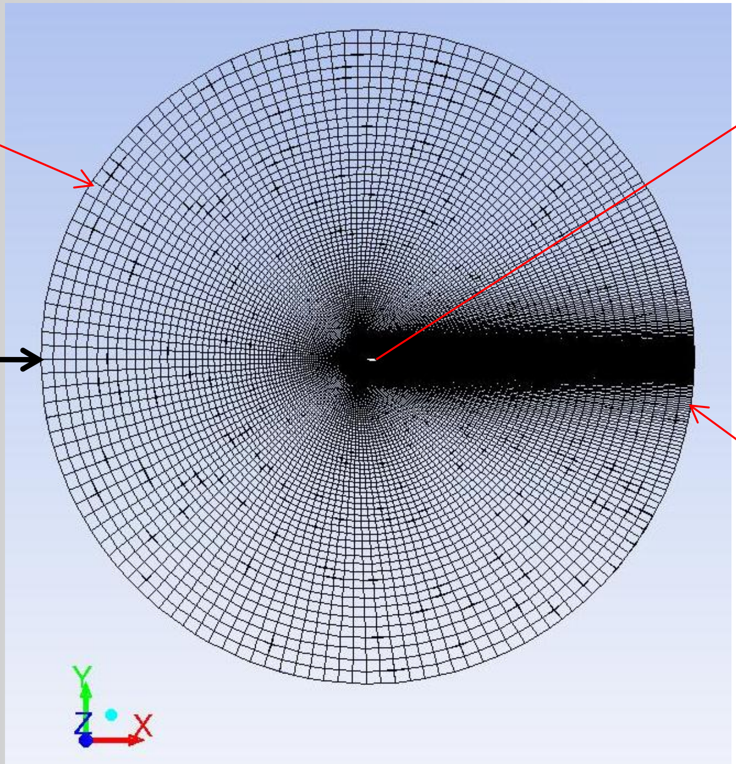
- Due to high Re number and moderate a, it looks still ok near trailing edge even though span=0.05c

NACA 0012 Airfoil Noise

- NACA 0012: $Re_{chord} = 1.1 \cdot 10^6$

Velocity inlet

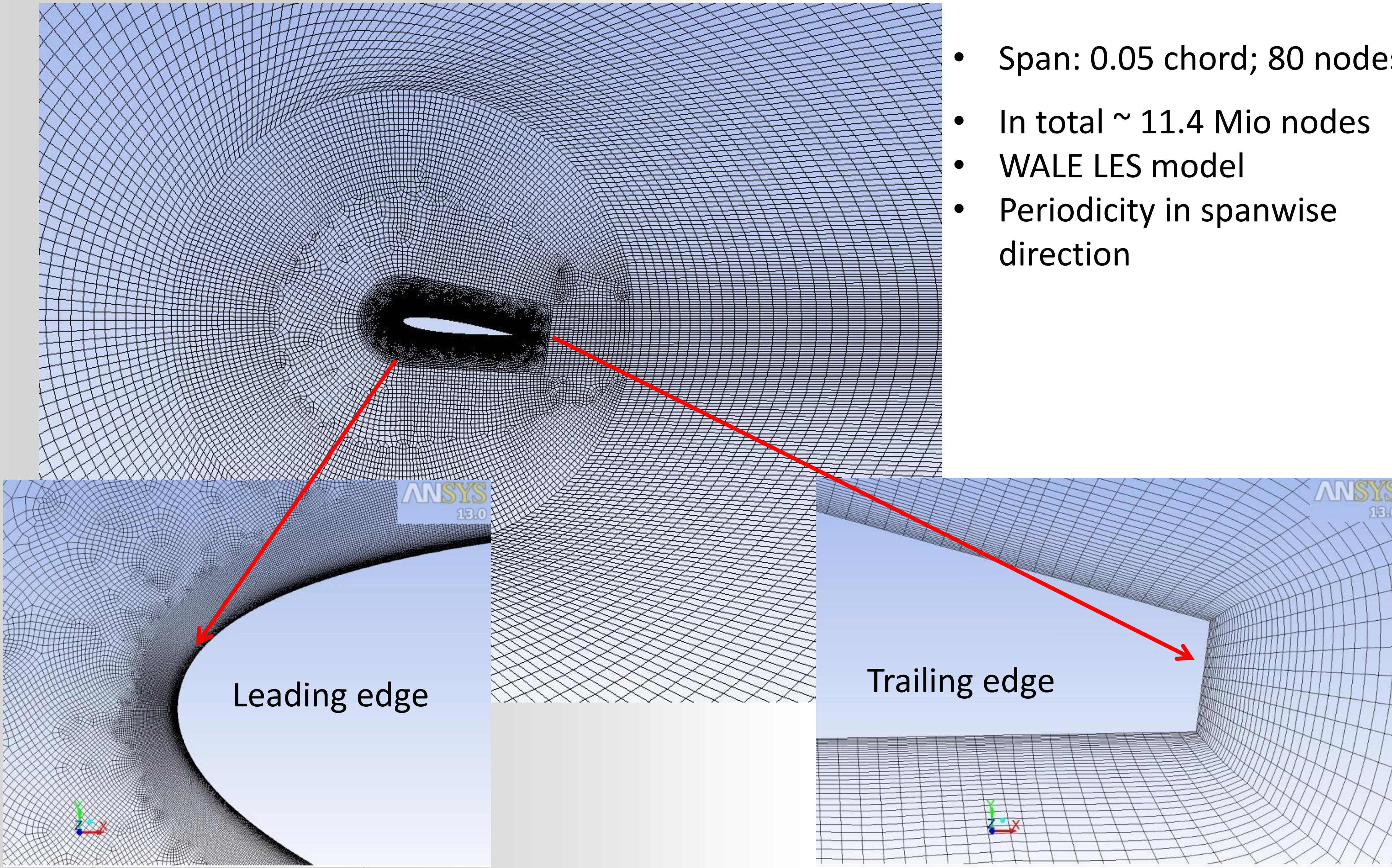
71.3 m/s



Airfoil rotated by 7.3 degree

Pressure outlet

WB Unstructured Hex Mesh

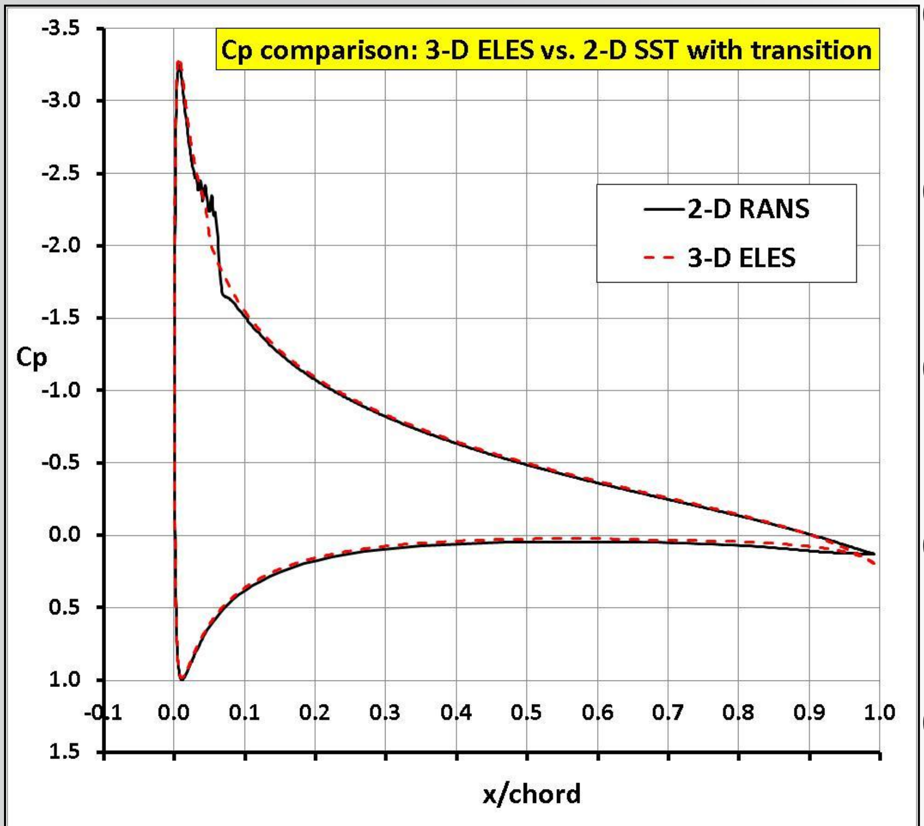


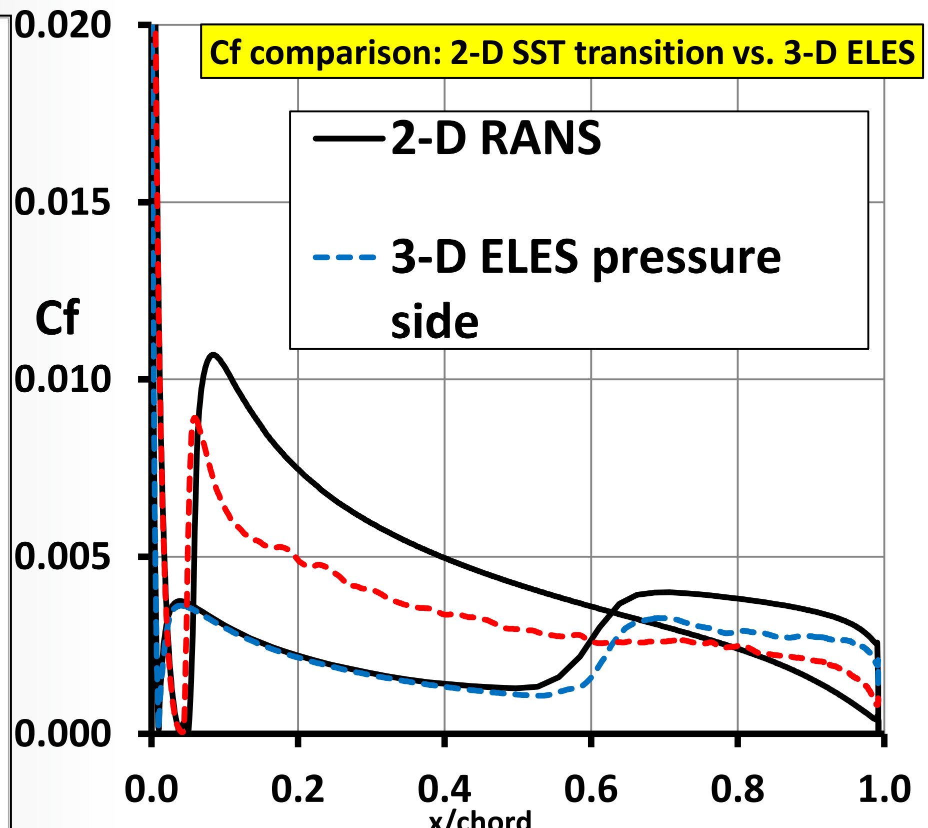
- Span: 0.05 chord; 80 nodes
- In total ~ 11.4 Mio nodes
- WALE LES model
- Periodicity in spanwise direction

5%chord, 11M cells, Δt=1.5 μs

Pressure and skin friction coefficients

Even on this grid cf is too low -> WMLES (see later)





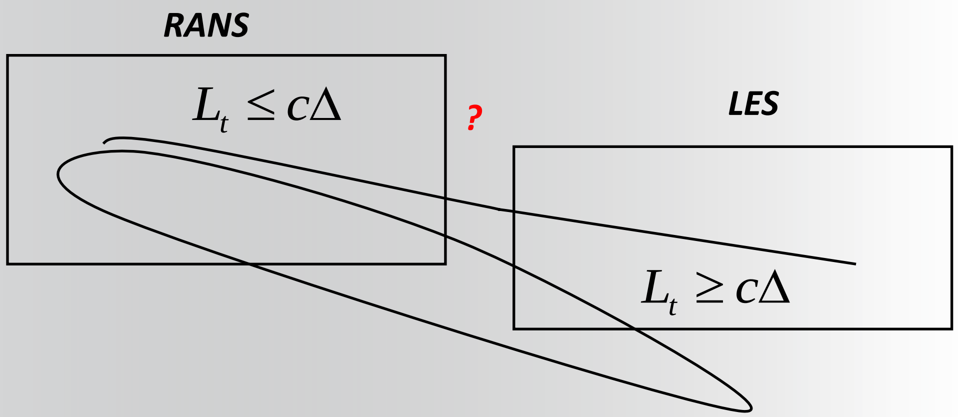
Detached Eddy Simulation (DES)

Hybrid Model:

- RANS equations in boundary layer.
- LES „ detached “ regions.

Switch of model:

- Based on ratio of turbulent length-scale to grid size.
- Different numerical treatment in RANS and LES regions.



- **Overcomes threshold limit of LES**
- **Explicit grid sensitivity in RANS region**
- **Open question concerning transition region between RANS and LES**

DES for SST – Strelets (2000)

- **k-equation RANS**

$$\frac{\partial(\rho k)}{\partial t}+\frac{\partial(\rho \bar{U}_j k)}{\partial x_j}=P_k-\rho\frac{k^{3/2}}{L_t}+\frac{\partial}{\partial x_j}\left[(\mu+\frac{\mu_t}{\tilde{\sigma}_\kappa})\frac{\partial k}{\partial x_j}\right] \qquad L_t=\frac{\sqrt{k}}{\beta^*\omega}$$

- **k-equation LES**

$$\frac{\partial(\rho k)}{\partial t}+\frac{\partial(\rho \bar{U}_j k)}{\partial x_j}=P_k-\rho\frac{k^{3/2}}{C_{DES}\Delta}+\frac{\partial}{\partial x_j}\left[(\mu+\frac{\mu_t}{\tilde{\sigma}_\kappa})\frac{\partial k}{\partial x_j}\right] \qquad \Delta=\max(\Delta x,\Delta y,\Delta z)$$

- **k-equation DES**

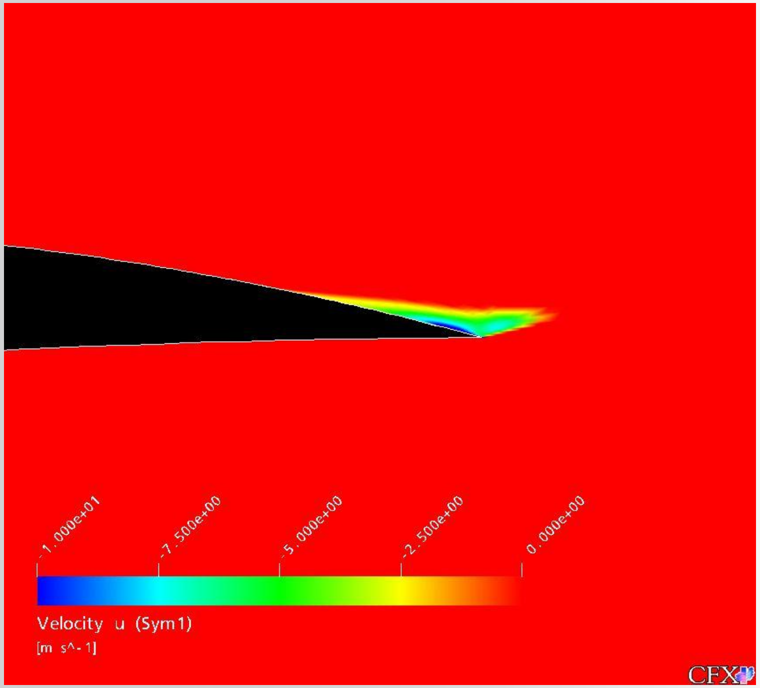
$$\frac{\partial(\rho k)}{\partial t}+\frac{\partial(\rho \bar{U}_j k)}{\partial x_j}=P_k-\rho\frac{k^{3/2}}{\min\left(L_t;C_{DES}\Delta\right)}+\frac{\partial}{\partial x_j}\left[(\mu+\frac{\mu_t}{\tilde{\sigma}_\kappa})\frac{\partial k}{\partial x_j}\right]$$

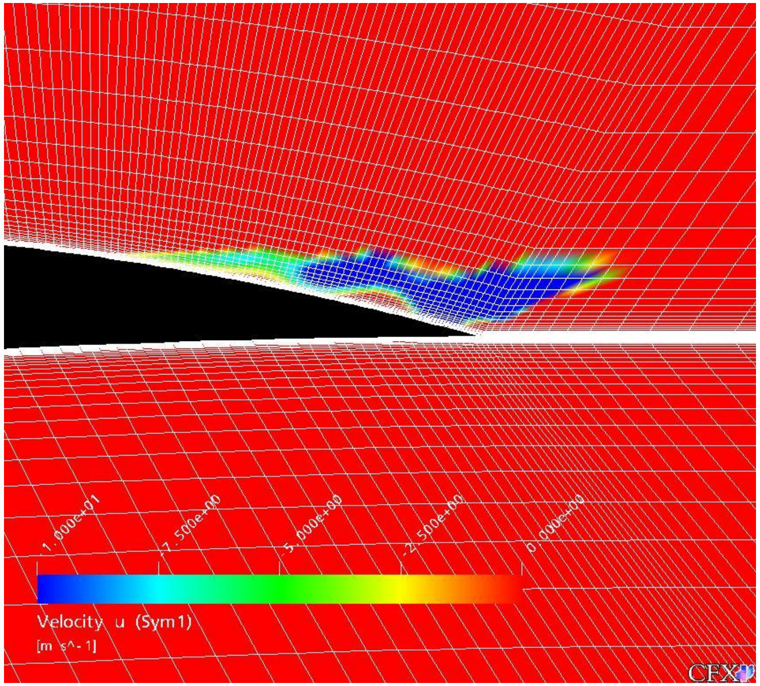
Grid Sensitivity with DES Model

SST model

Separation Zone

SST-DES-SPTU model





Requirement: $\Delta x > \delta$

Alternative – Shielding functions – Delayed DES (DDES)

DES for SST – Delayed DES (DDES)

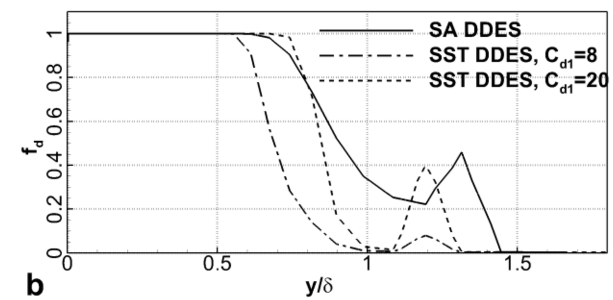
- DDES – provides shielding functions which keep DES in RANS mode in attached boundary layers even for fine grids:

- Destruction term original DES-SST model :

$$E = \rho \frac{k^{3/2}}{\min\left(L_t; C_{DES}\Delta\right)} = \rho \frac{k^{3/2}}{L_t \min\left(1; C_{DES}\Delta / L_t\right)} = \rho \frac{k^{3/2}}{L_t} \max\left(1; \frac{L_t}{C_{DES}\Delta}\right)$$

- DES function used for SST model to shield boundary layer from DES impact (Delayed DES – DDES)

$$F_{DES-CFX} = \max\left(\frac{L_t}{C_{DES}\Delta} \cdot \left(1 - F_{DDES}\right), 1\right); \quad F_{SST} = 0, F_1 \; or \; F_2, F_{DDES}$$



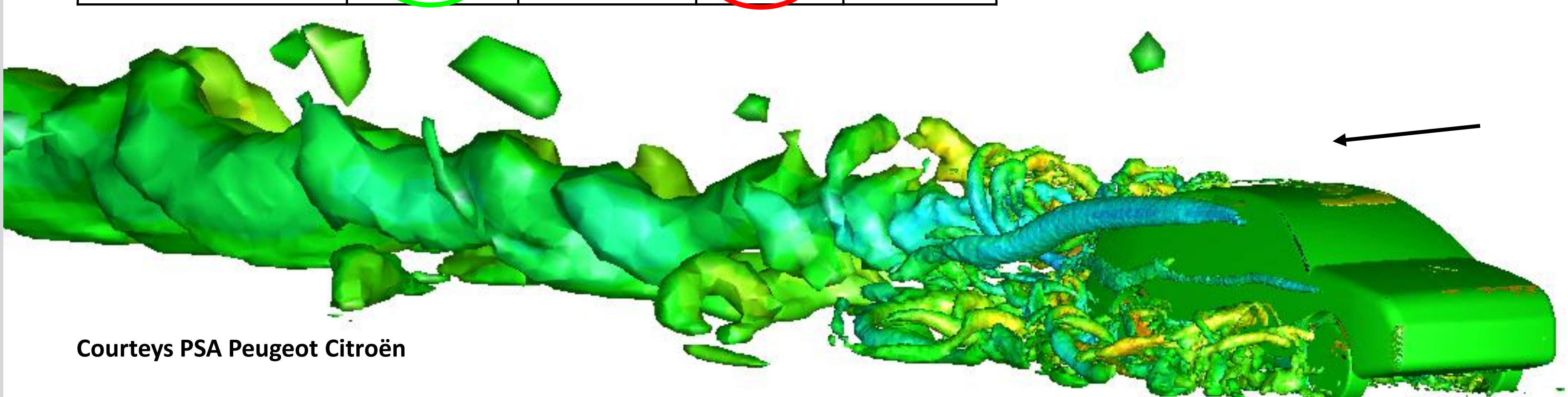
- Shielding up to: $\Delta_{\max} > 0.1 \cdot \delta_{BL}$

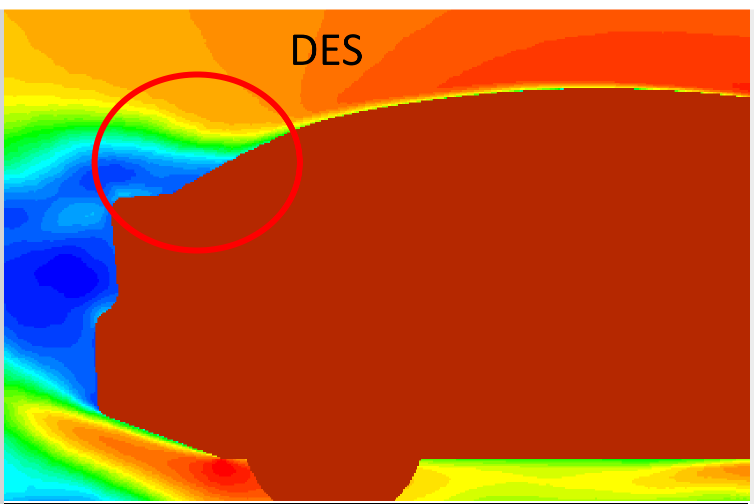
DES/DDES of Separated Flow around a realistic Car model exposed to Crosswind

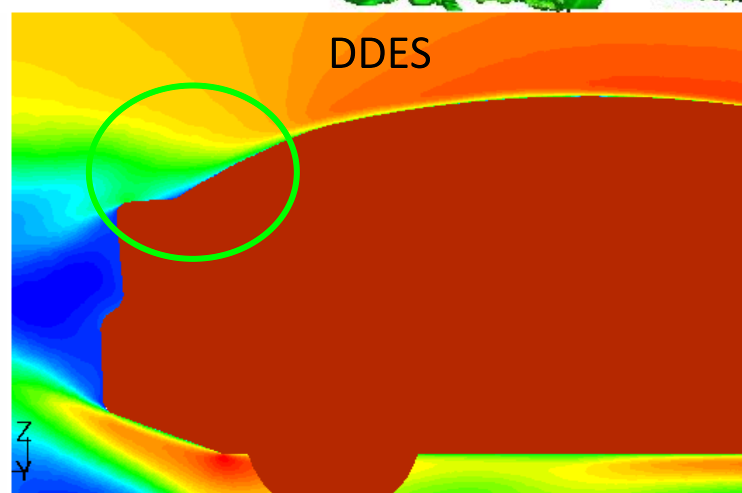
Model	Exp.	DDES	DES	LES
Drag (SCx)	0.70	0.71	0.75	0.69

U=40 m/s Yaw angle 20°

Re_H~10^6

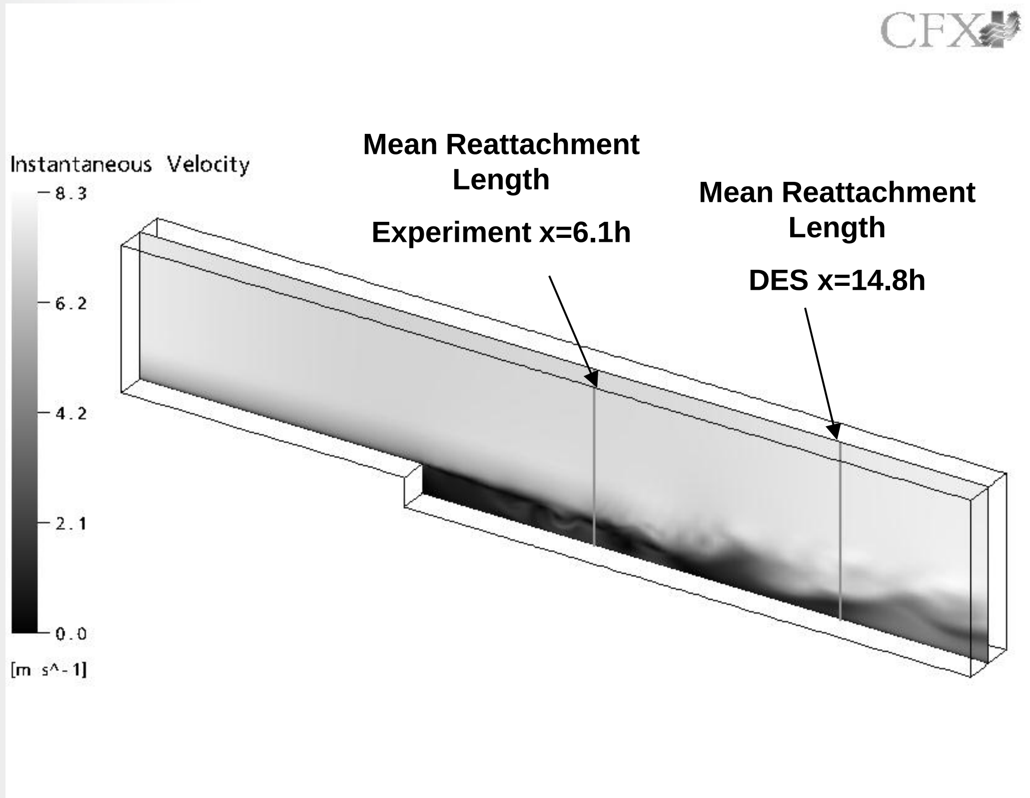






DES Problem “Grey Areas”

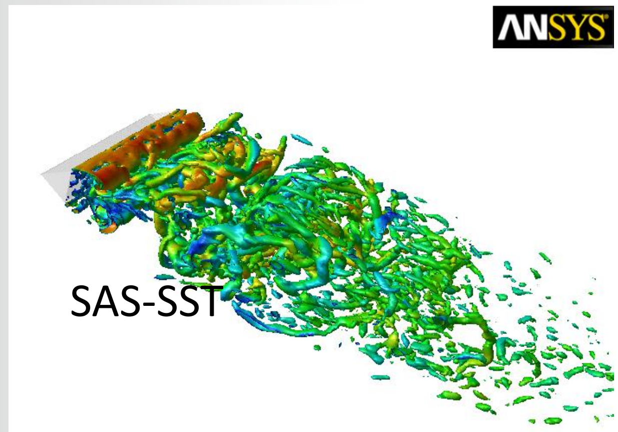
- Model has not fully switched between RANS and LES mode
  - Grid resolution to low
  - Instability too weak
- Balance of resolved and unresolved portions of the flow is not achieved – loss of turbulent kinetic energy
- Undefined model
- Further mesh refinement required

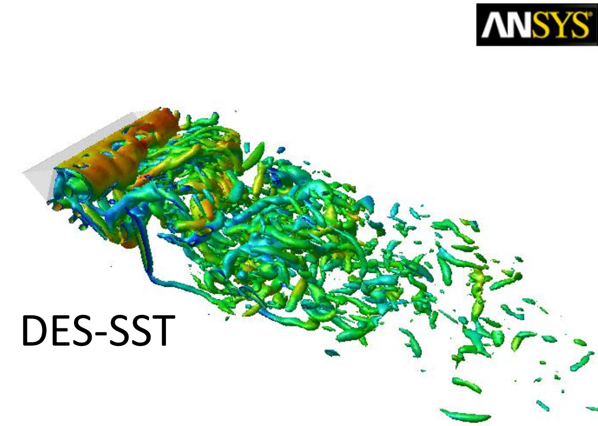


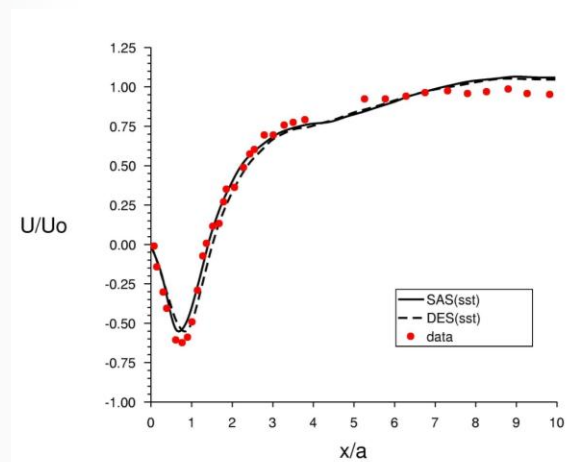
Courtesy: Herr Sohm – BMW AG

SAS and DES Model for triangular Cylinder

- SAS and DDES work well for strongly unstable flows
- Often produce very similar results
- Both, SAS and DES rely on flow instability to quickly produce unsteady turbulence – this works well for many flows



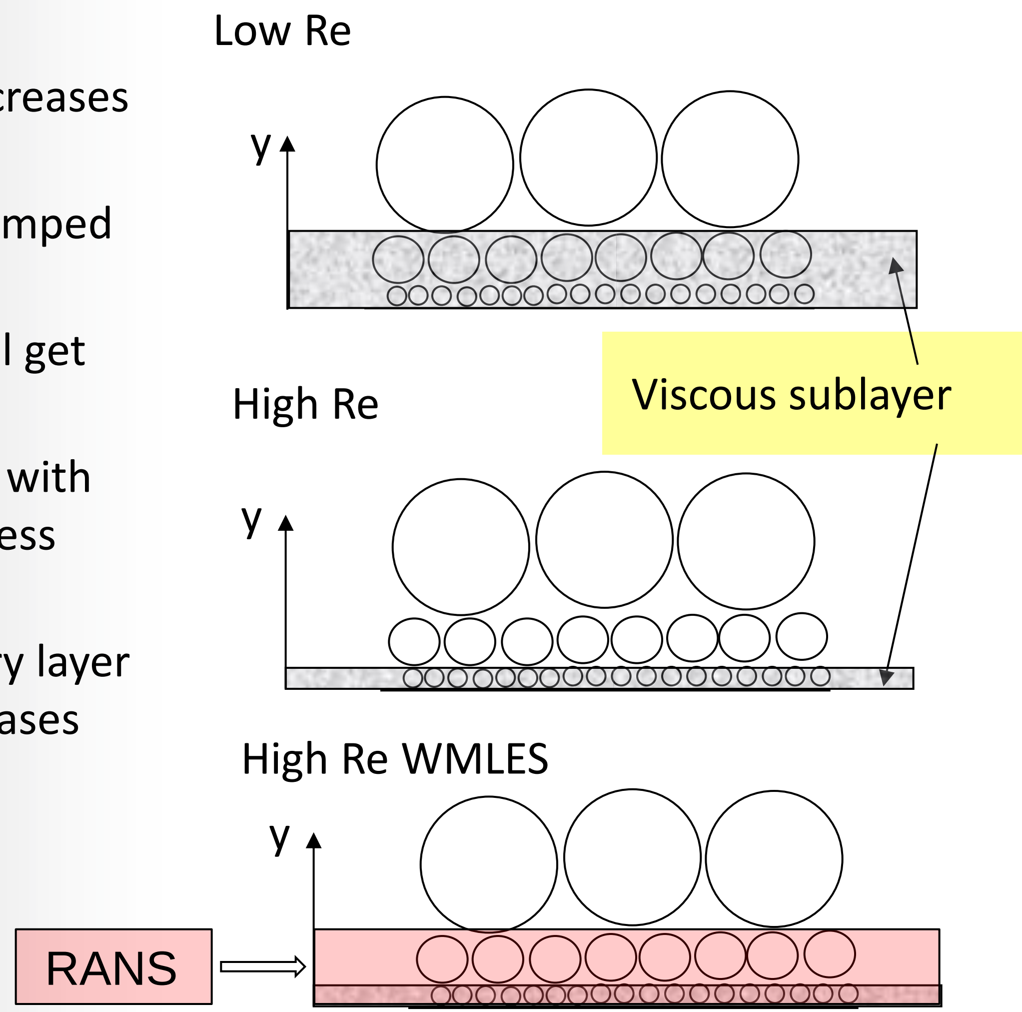




WMLES: Near Wall Scaling

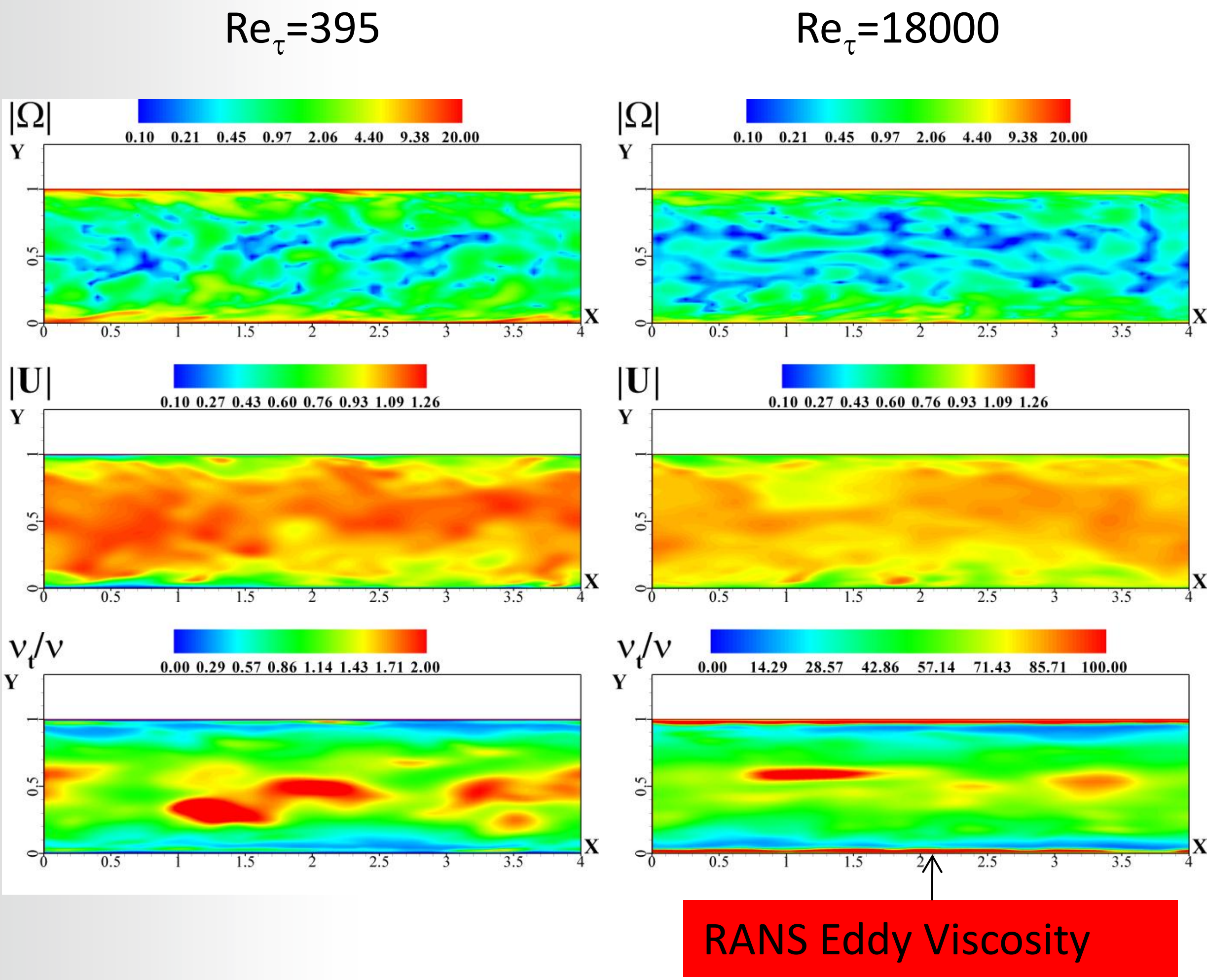
$$L_t = \kappa y$$

- 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



WMLES – Channel Flow at Different Re Numbers

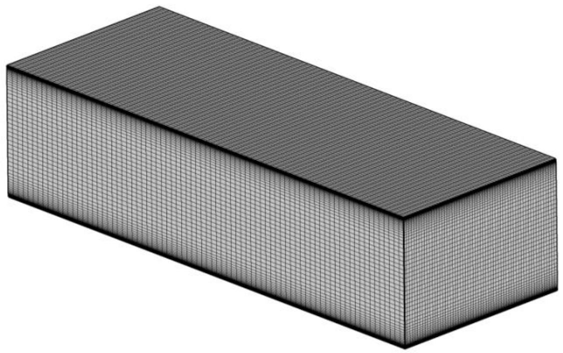
- **Solutions at very different Re numbers look essentially identical**
- **Differences can only be seen near the wall.**
- **Visible is higher Eddy-Viscosity for higher Re number close to wall**



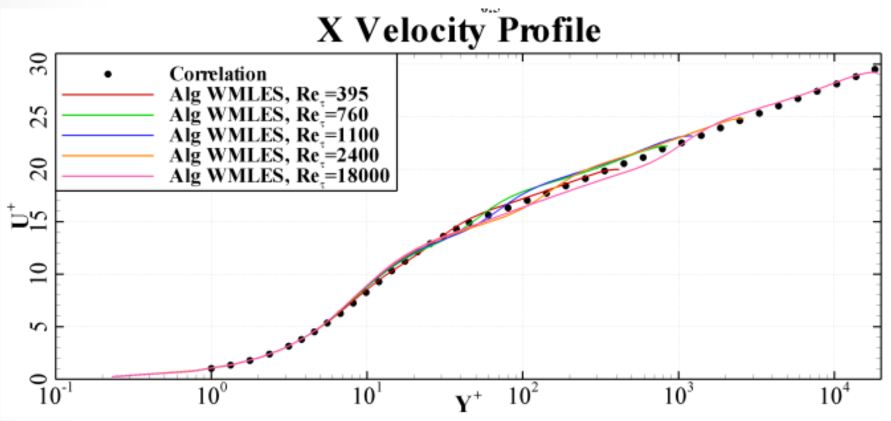
  October 17, 2013

WMLES – Channel Flow Tests

Re_τ	Cells Number	LES Cells Number	Nodes Number	ΔX^+	ΔZ^+
395	384 000	384 000	81×81×61	40.0	20.0
760	480 000	1 500 000	81×101×61	76.9	38.5
1100	480 000	4 000 000	81×101×61	111.4	55.7
2400	528 000	19 000 000	81×111×61	243.0	121.5
18000	624 000	1 294 676 760	81×131×61	1822.7	911.4



- Very large savings between WMLES and wall-resolved LES
- Alternative is LES with wall functions – however Δx^+ and Δz^+ are a function of Δy^+



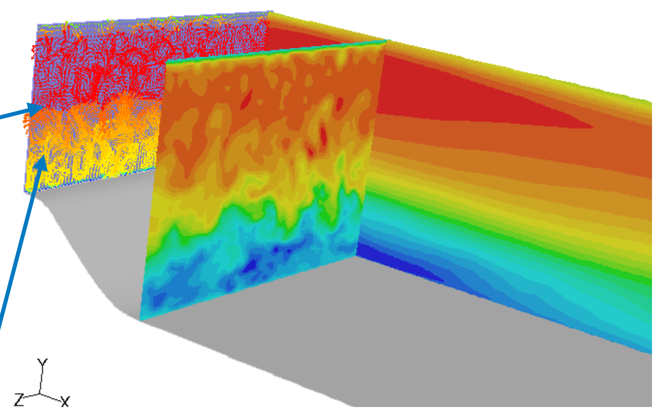
Vortex Method

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

$$\omega(\mathbf{x},t)=\sum_{k=1}^{N}\Gamma_k(t)\,\eta\left(\left|\mathbf{x}-\mathbf{x}_k\right|,t\right)$$

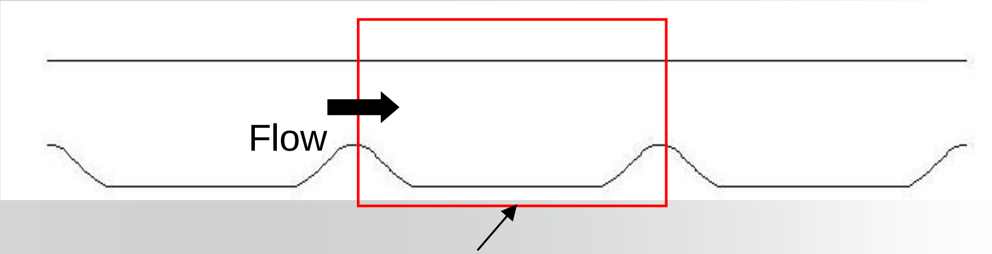
- Velocity field computed using the Biot-Savart's law

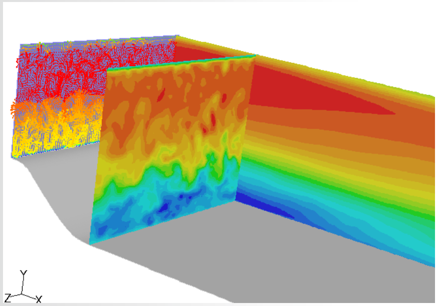
$$\mathbf{u}(\mathbf{x},t)=-\frac{1}{2\pi}\iint\frac{(\mathbf{x}-\mathbf{x}')\times\omega(\mathbf{x}')\mathbf{e}_z}{\left|\mathbf{x}-\mathbf{x}'\right|^2}\,d\mathbf{x}'$$



Vortex Method

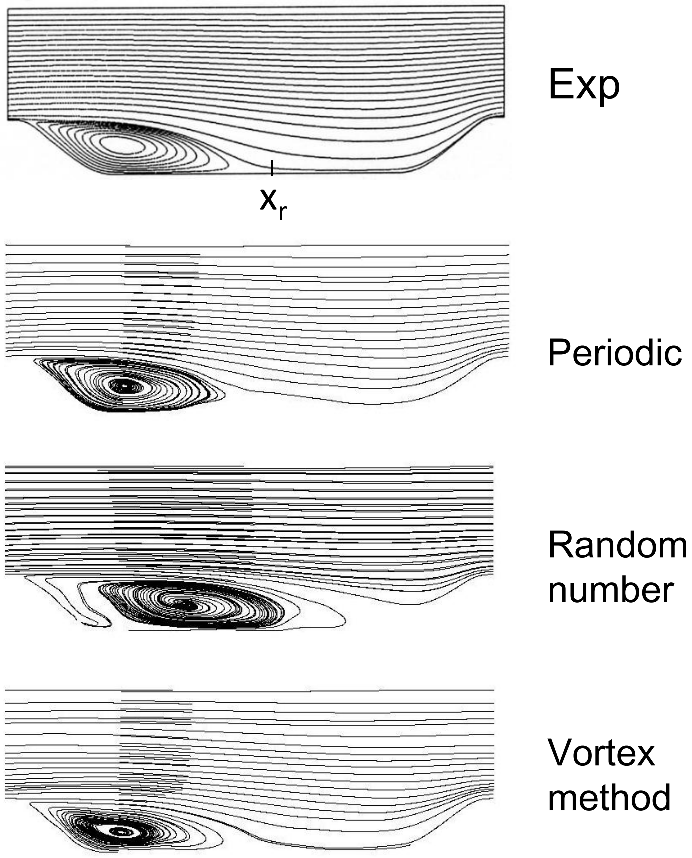
3-D Wavy Channel (Re_H = 10,600)
Mathey and Cokljat (2005)





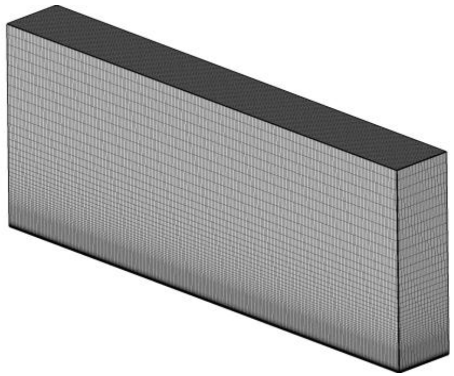
LES predictions of the reattachment point

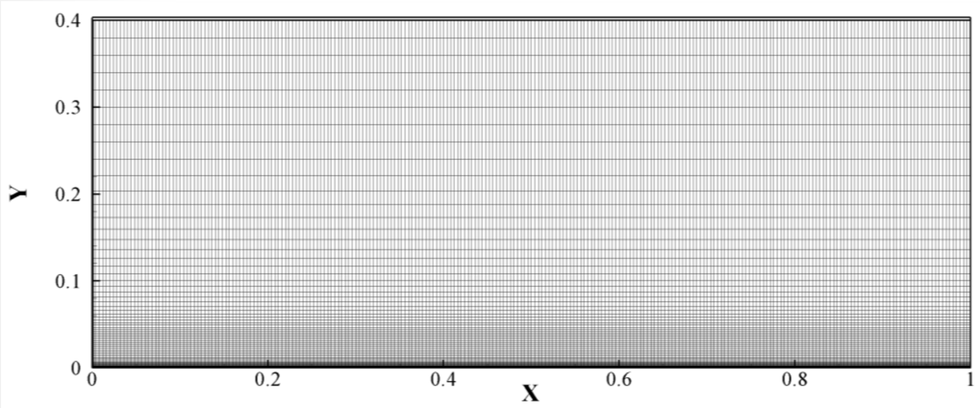
	X_r
Exp.	4.7 h
Periodic	5. H
VM	5.2 h
Random	7.7 h



WMLES – Flat Plate Grid

- Geometry and Grid
  - L x 0.4 L x 0.1 L (Streamwise, Normal, Spanwise)
  - Approximately 3 δ spanwise (δ_0=0.032)
  - Grid ~ 1Million cells (see table)
  - Y+~0.05 (to allow for higher Re numbers)
  - Expansion factor 1.15
  - For each boundary layer thickness δ one needs ~10x40x20 cells

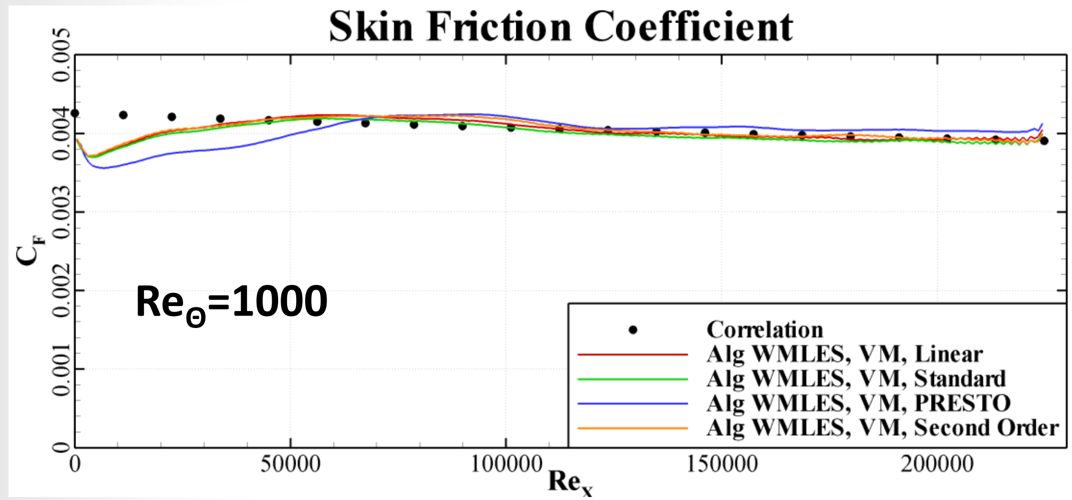


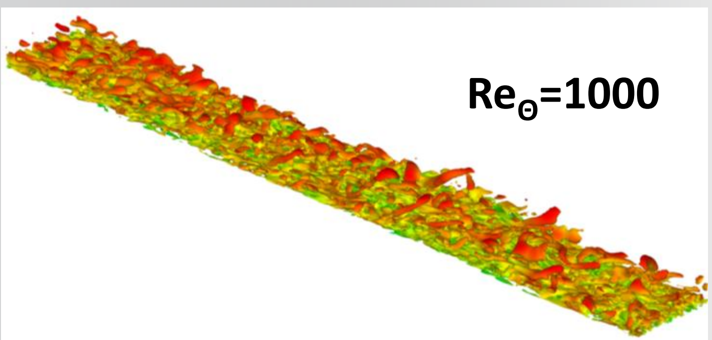


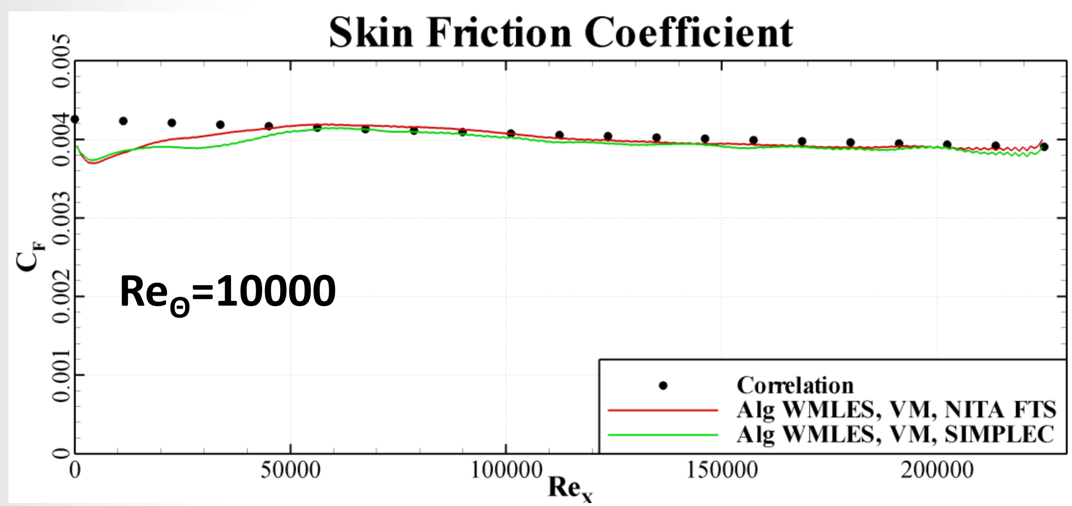
Re_Θ	Cells Number	Nodes Number	ΔX^+	ΔY^+	ΔZ^+
1000	1 085 000	251×71×63	68	0.05 ÷ 300	34
10000	1 085 000	251×71×63	520	0.4 ÷ 2300	307

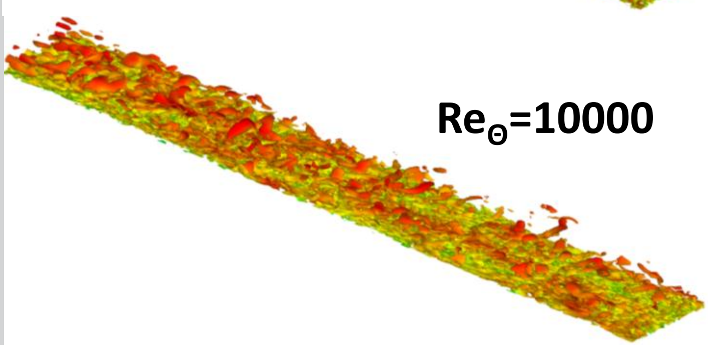
WMLES – Boundary Layer

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





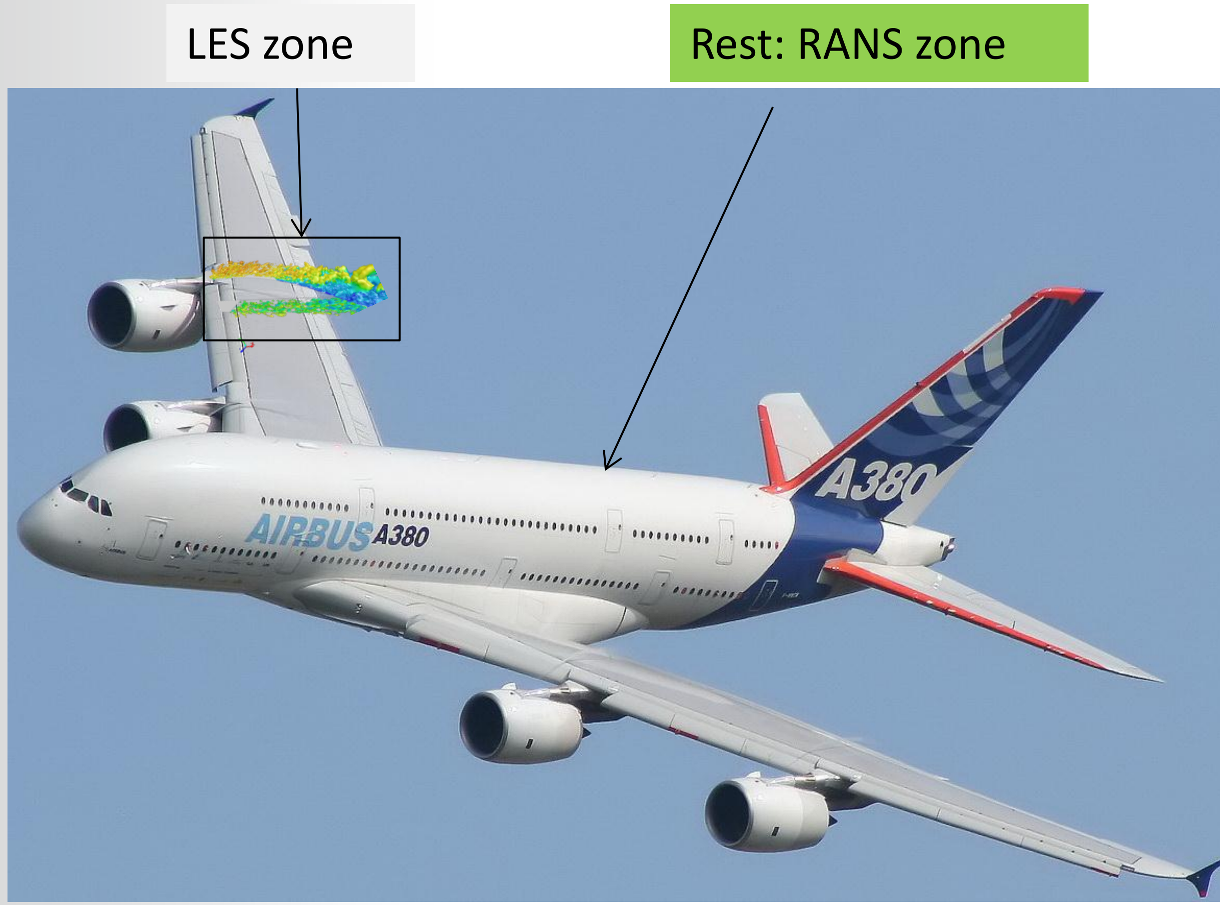




ANSYS

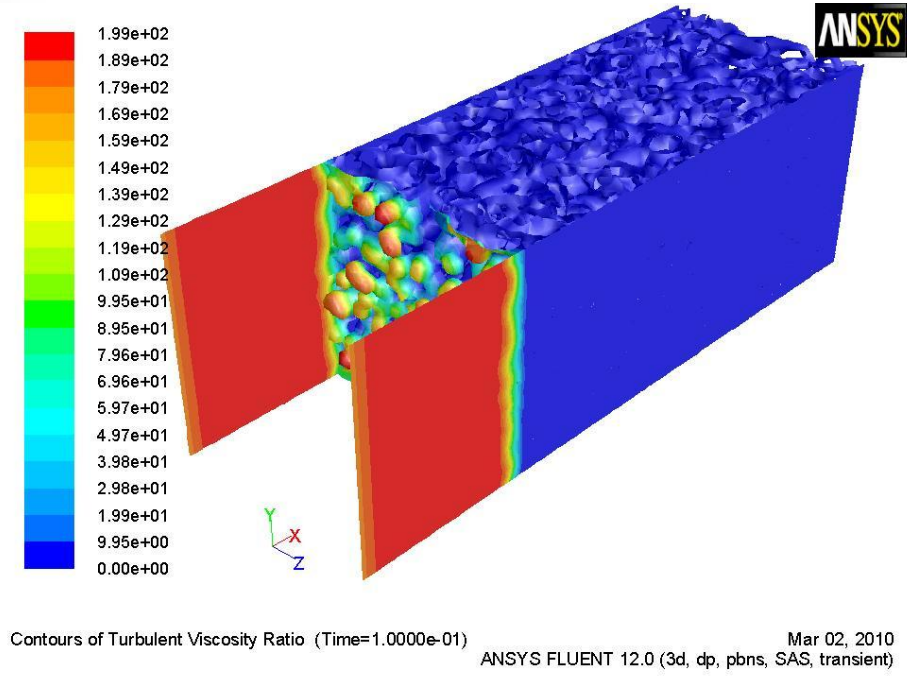
Embedded/Zonal Large Eddy Simulation (ELES, ZFLES)

- **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**



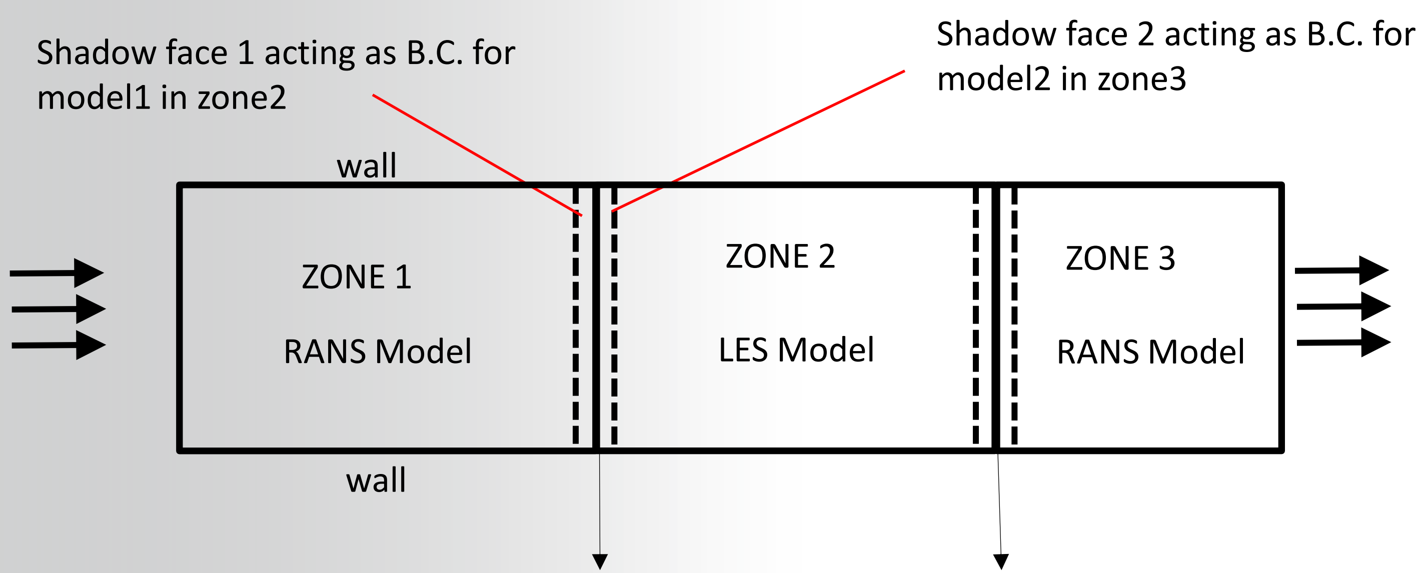
Embedded LES and Zonal Forced LES

- **In many flows an area where (WM)LES is required is embedded in a larger RANS region**
- **In such cases, a zonal method is advantageous**
- **RANS and LES regions are separately defined and use different models**
- **Synthetic turbulence is generated at the interface to convert RANS to LES turbulence**



Coupled Zonal Modelling

In ELES/ZFLES e.g. MODEL2 can be LES turbulence model embedded in a RANS or SAS model (MODEL1), or vice versa

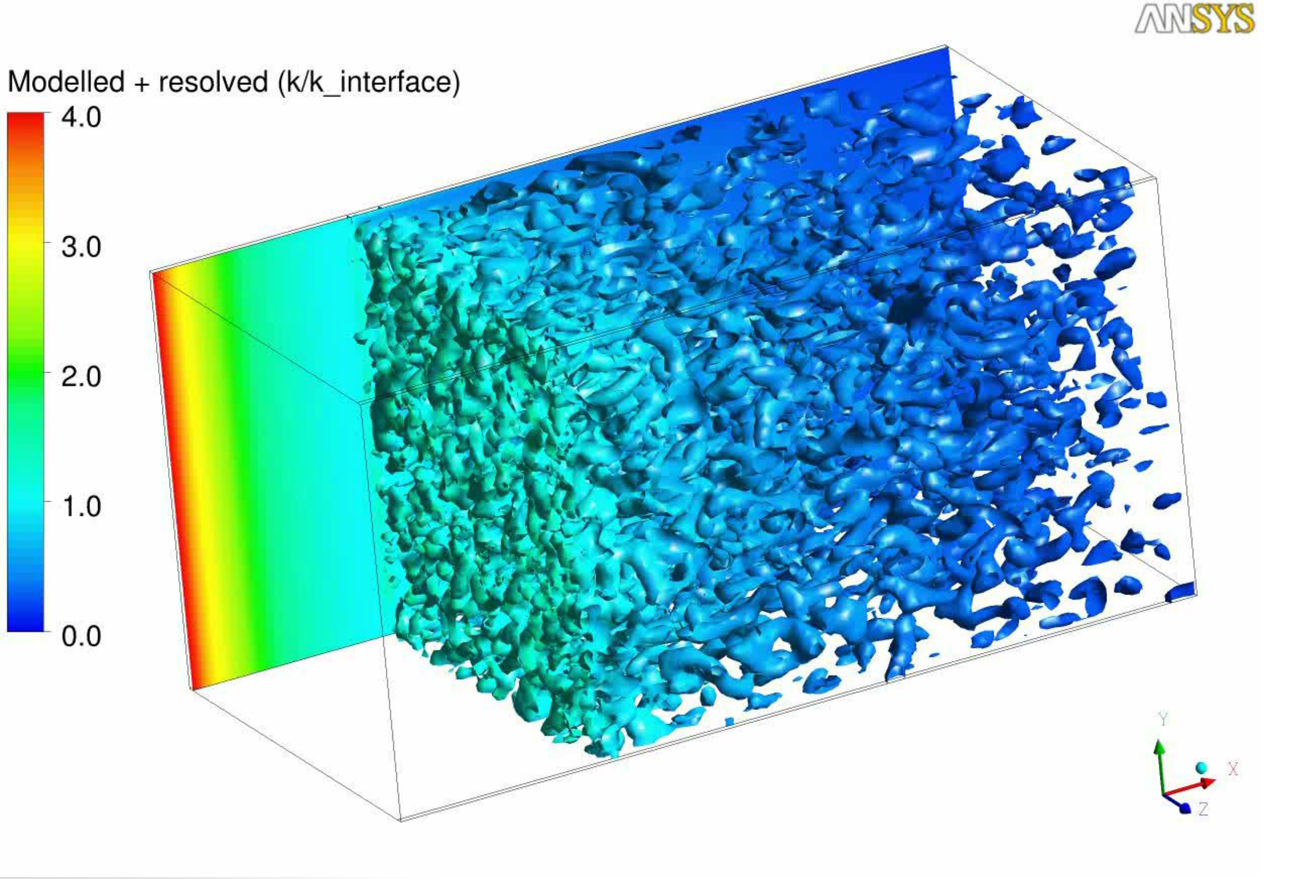


There is STRONG need for model interaction at this interface since models are different in Zone 2 → 3 and Zone 3 → 4

Zonal LES: Test cases

DIT-x: resolved 3-D structures

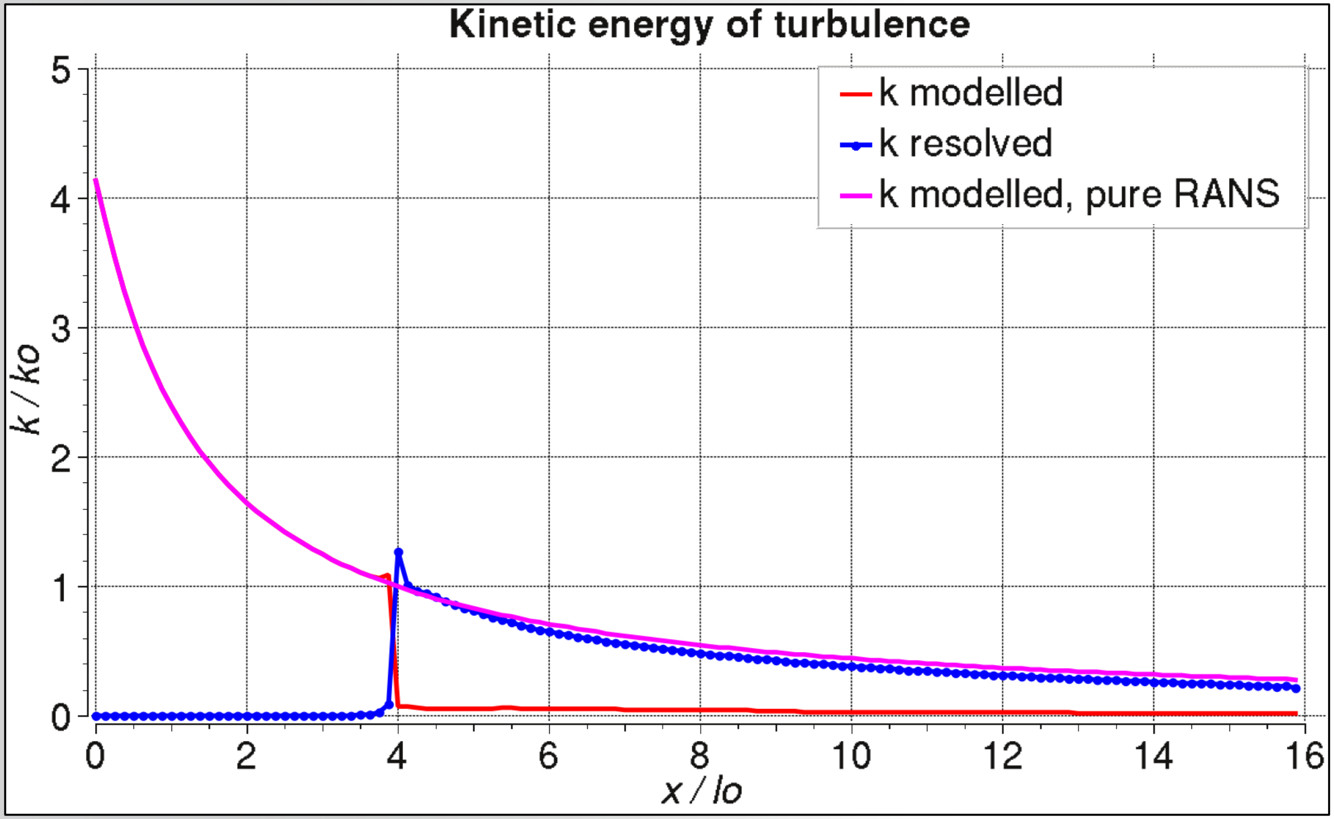
- Q criterion
- Bounded CD advection scheme (BCD)



Zonal LES: Test cases

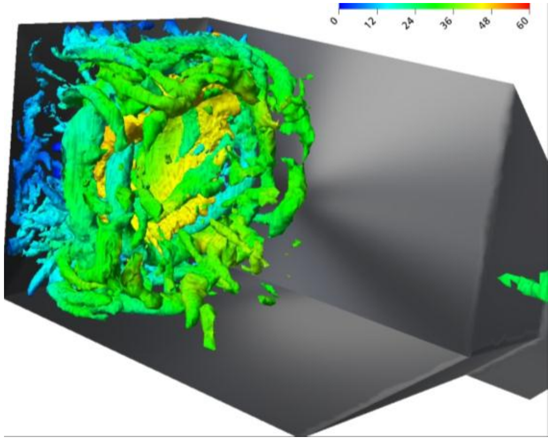
DIT-x: decay rate validation

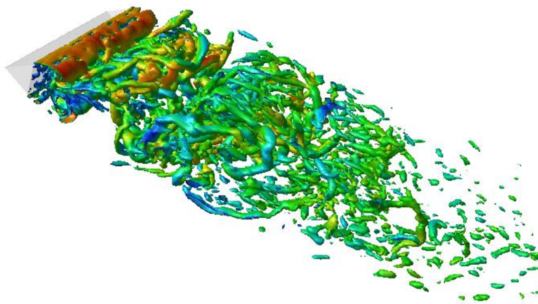
– **Modelled and resolved k**

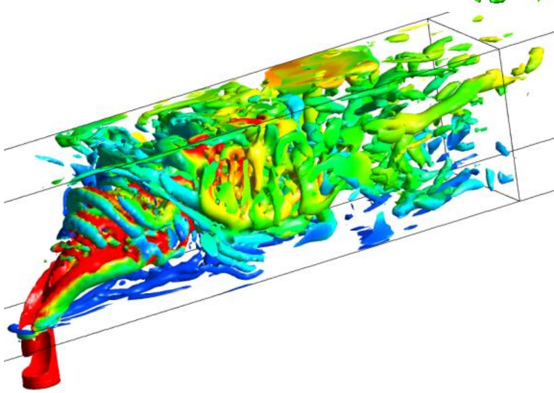


Flow Types: Globally Unstable Flows

- 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 (Δt, Δx)
  - **DDES:** Similar to SAS, but requires LES resolution for all free shear flows (Δt, Δx) (jets etc.)
  - **ELES:** Not really required as RANS model can cover boundary layers. Often difficult to place interfaces for synthetic turbulence.

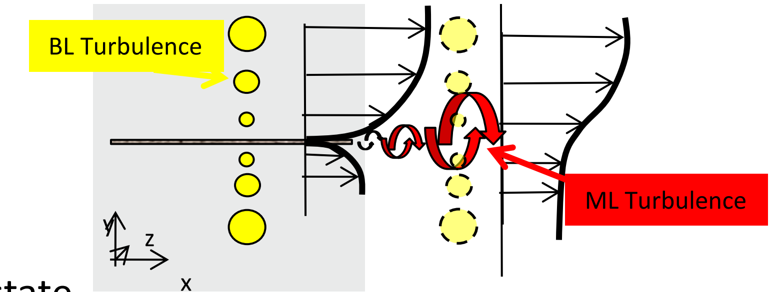




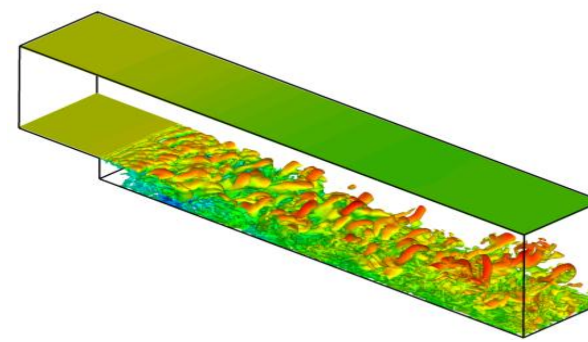


Green-recommended, Red=not recommended

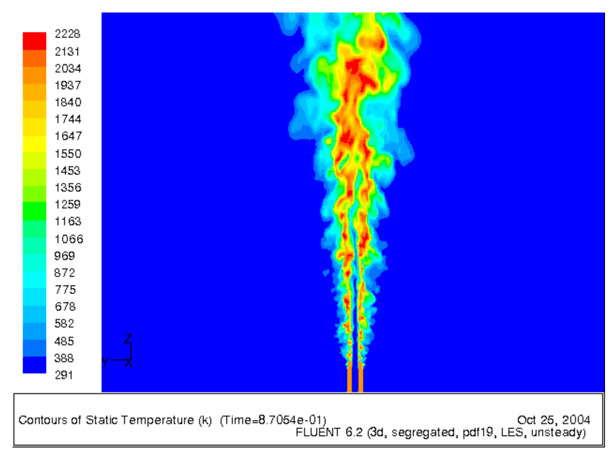
Flow Types: Locally Unstable Flows



- 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.



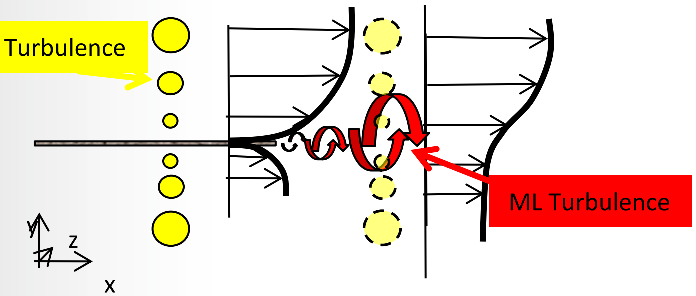
- Models
  - SAS: Stays in RANS mode. Covers upstream boundary layers in RANS mode. Can be triggered into SRS mode by RANS-LES interface.
  - DDES: Can be triggered to go into LES mode by fine grid and small Δt. Careful grid generation required. Covers upstream boundary layers in RANS mode.
  - ELES: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



Green-recommended, Red=not recommended

Flow Types: Locally Unstable Flows

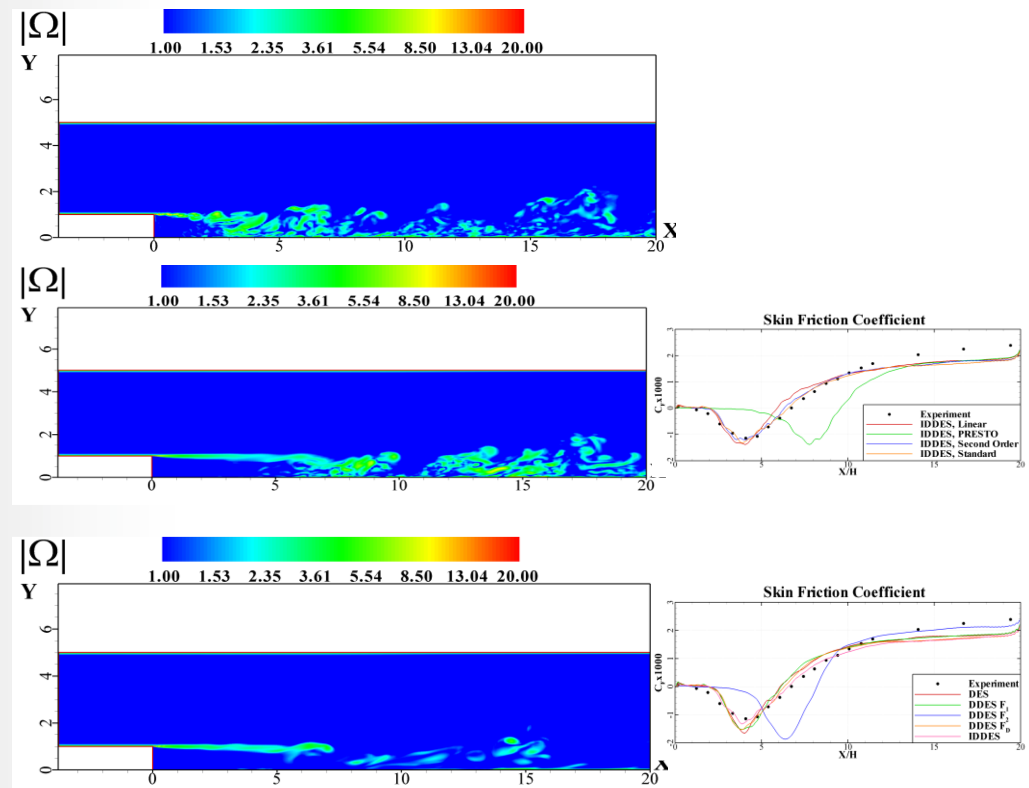
- Resolving flow instability in moderately unstable flows is demanding in terms of:
  - Grid resolution – needs to be of LES quality
  - Numerics – more demanding than fully turbulent LES
  - Shielding – balance between shielding and capturing instability
  - Difficult in complex industrial flows



Optimal

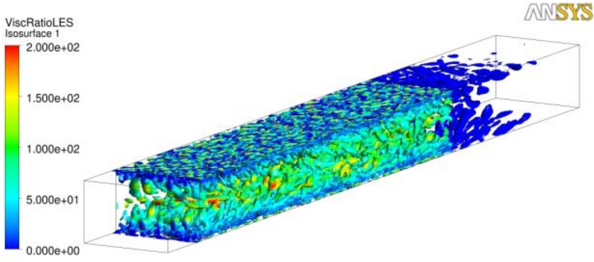
Numerics (PRESTO)

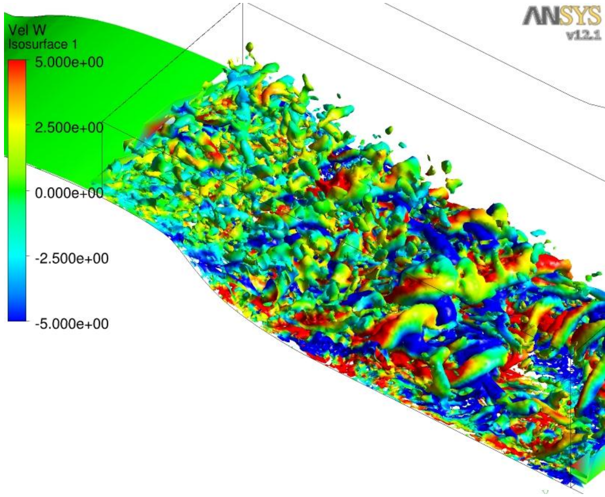
Shielding SST-F2



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 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 RANS mode. Synthetic turbulence RANS-LES interface.





Green-recommended, Red=not recommended

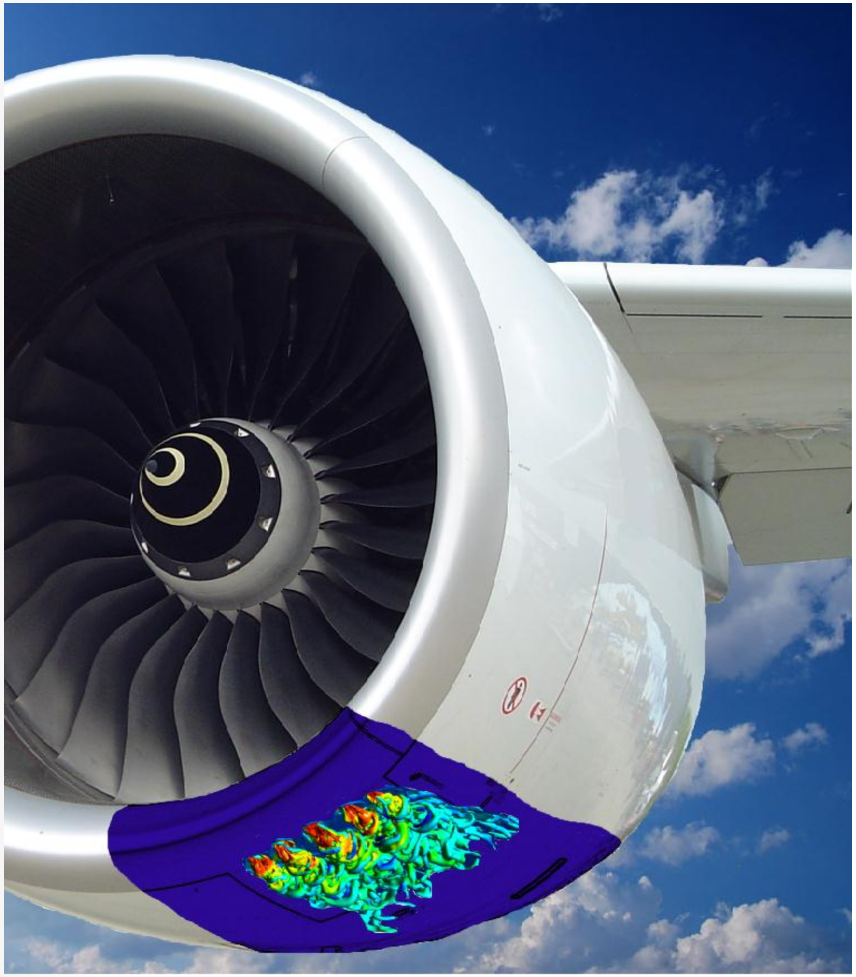
Globally Unstable Flow – Jets in Crossflow

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

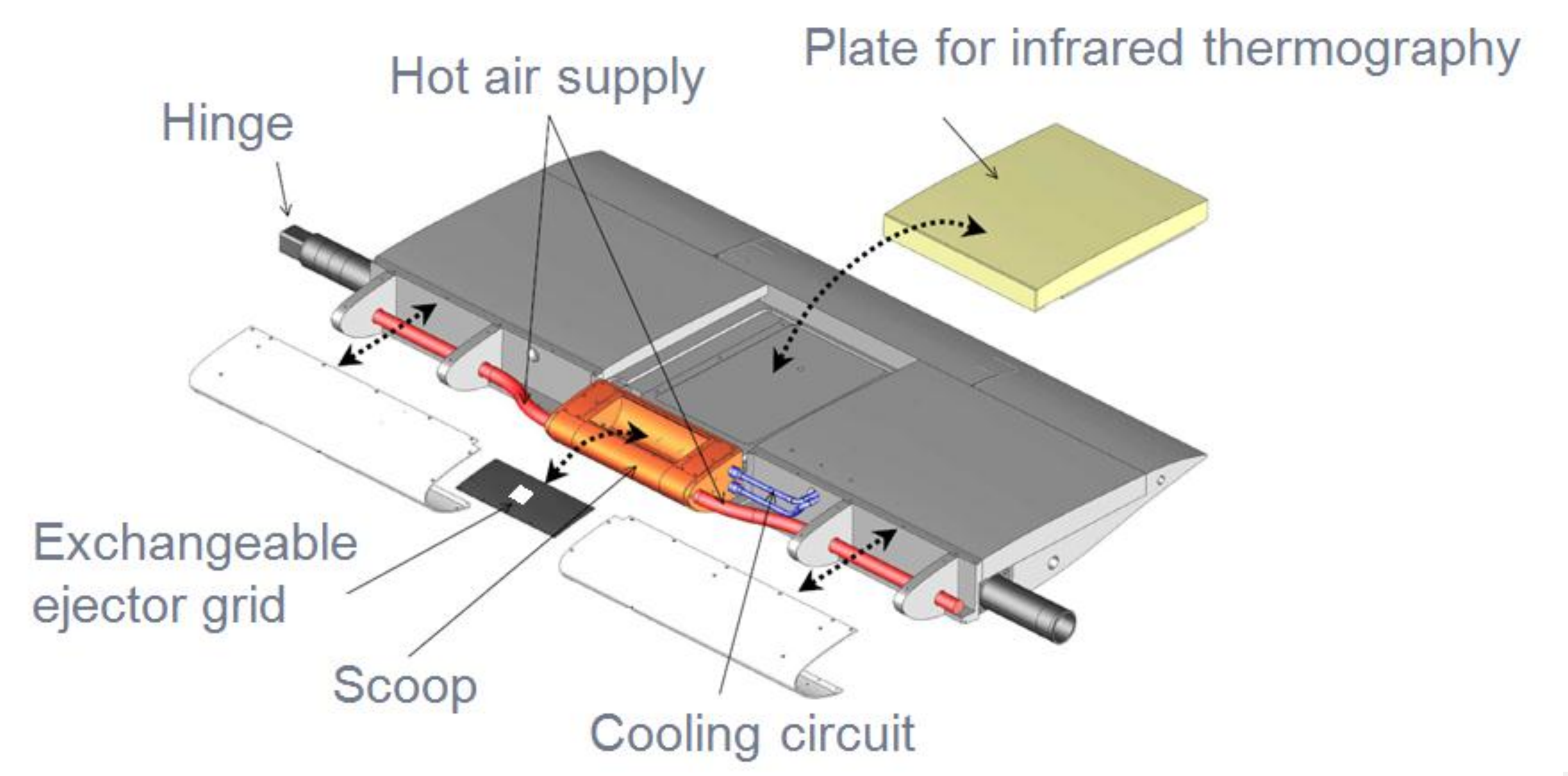
Problem:

- 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

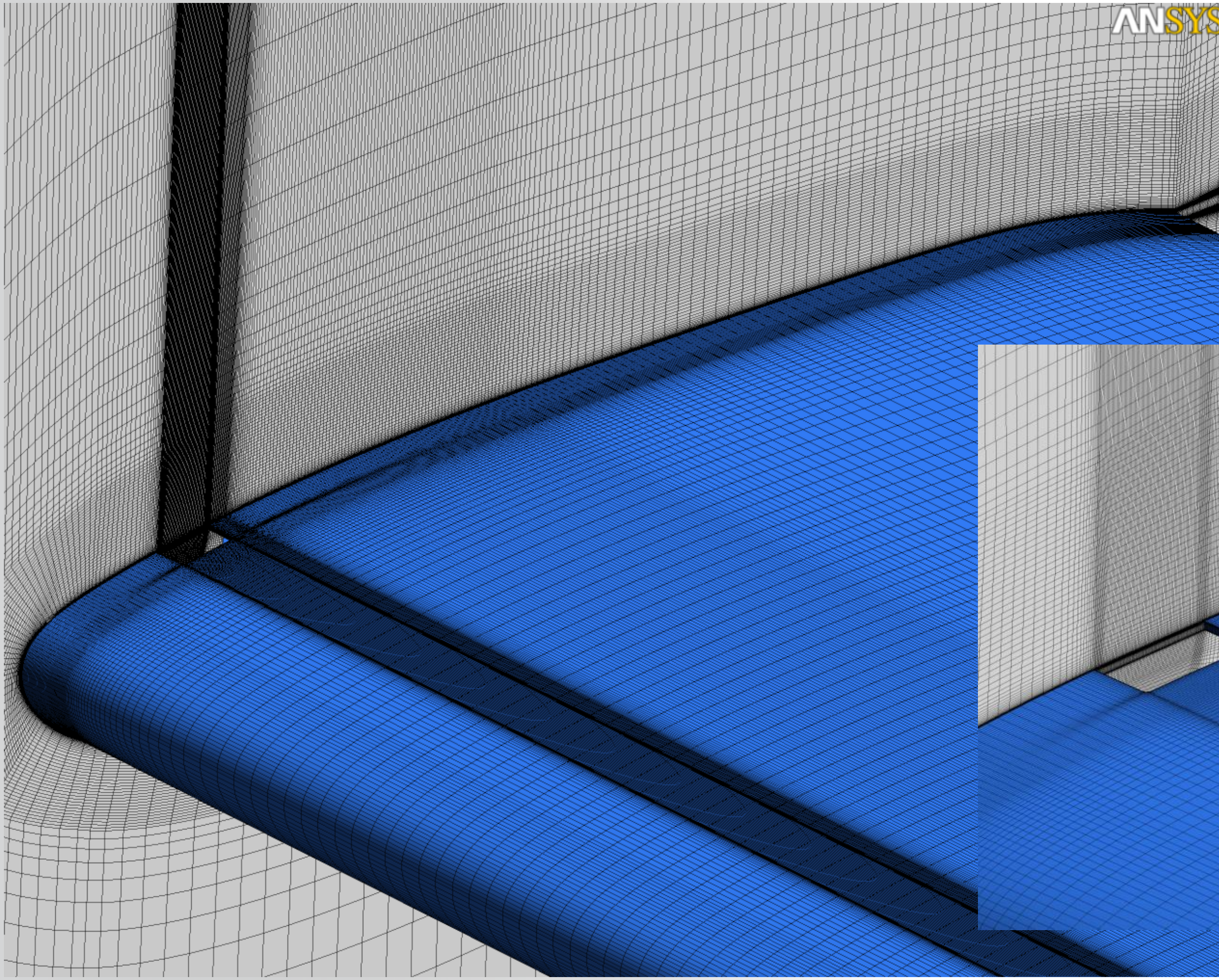
Generic Jet in Cross Flow Configuration



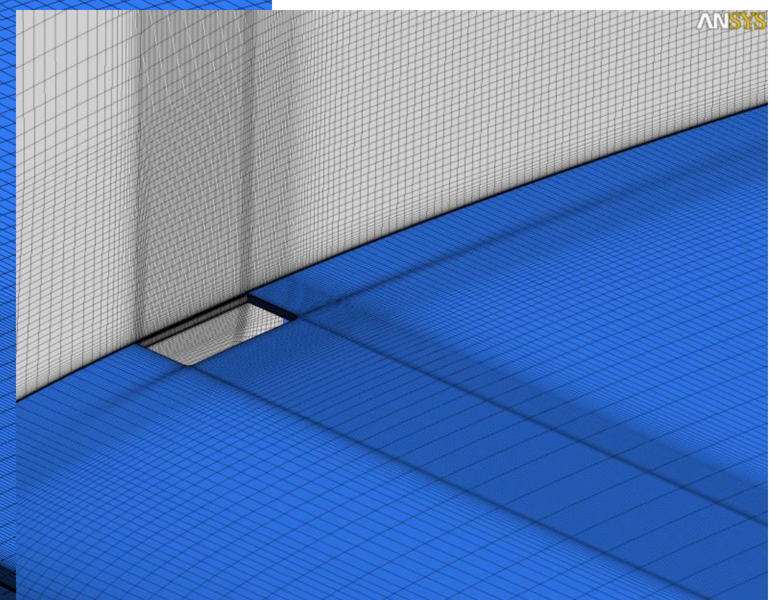
Infrared Thermography	Particle Image Velocimetry
Laser Doppler Anemometry	Hot and Cold Wire Measurements

Courtesy: Benjamin Duda, Airbus Toulouse

Hexahedral Mesh

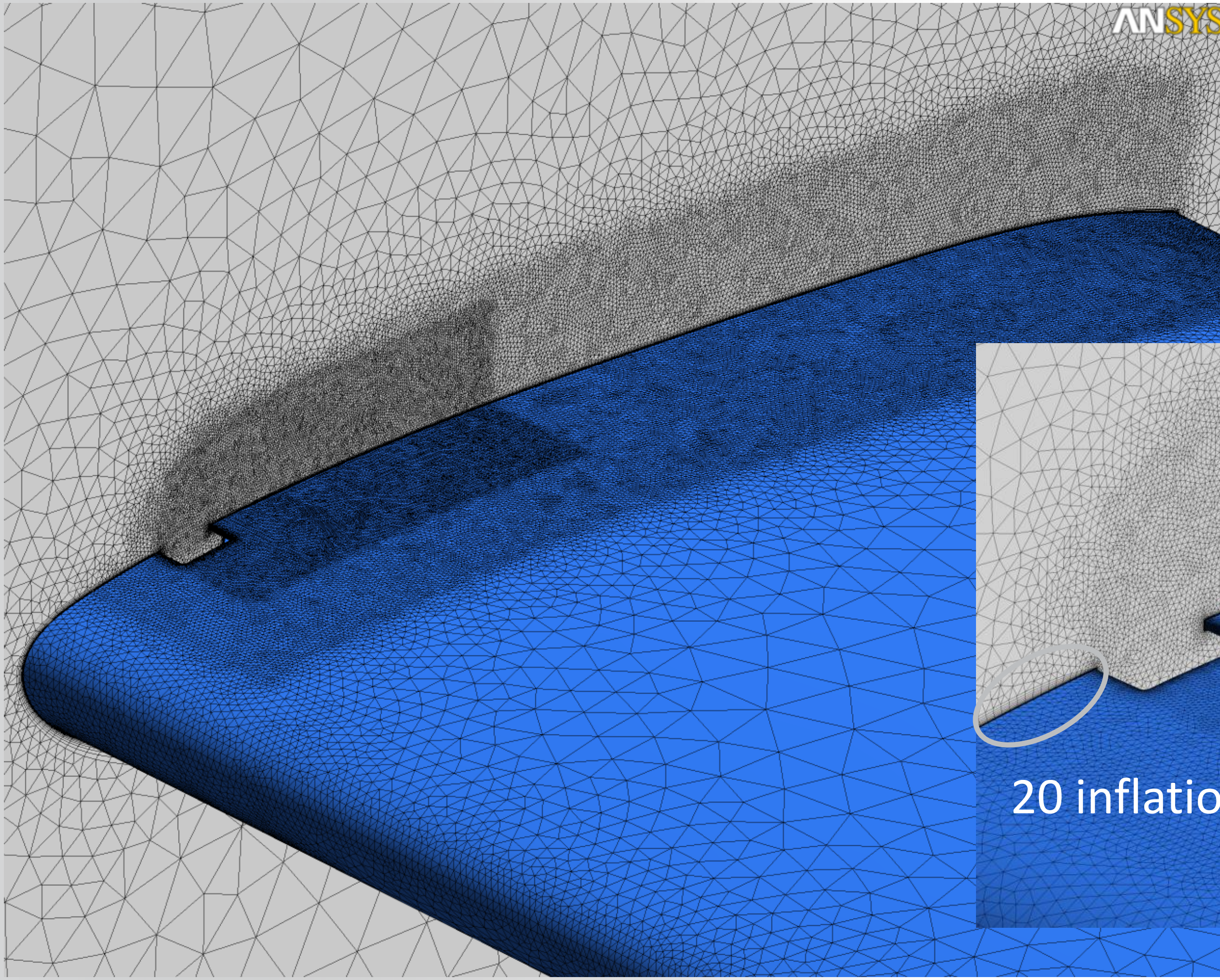


12,900,000 Elements
Min angle = 28.1°
Max AR = 3,500
Max VC = 10

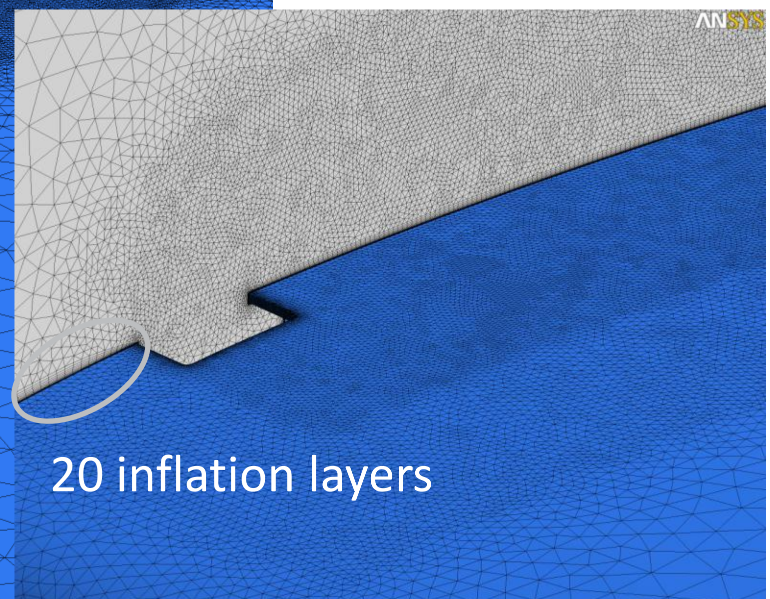


Courtesy: Benjamin Duda, Airbus Toulouse

Hybrid Tetrahedral Mesh



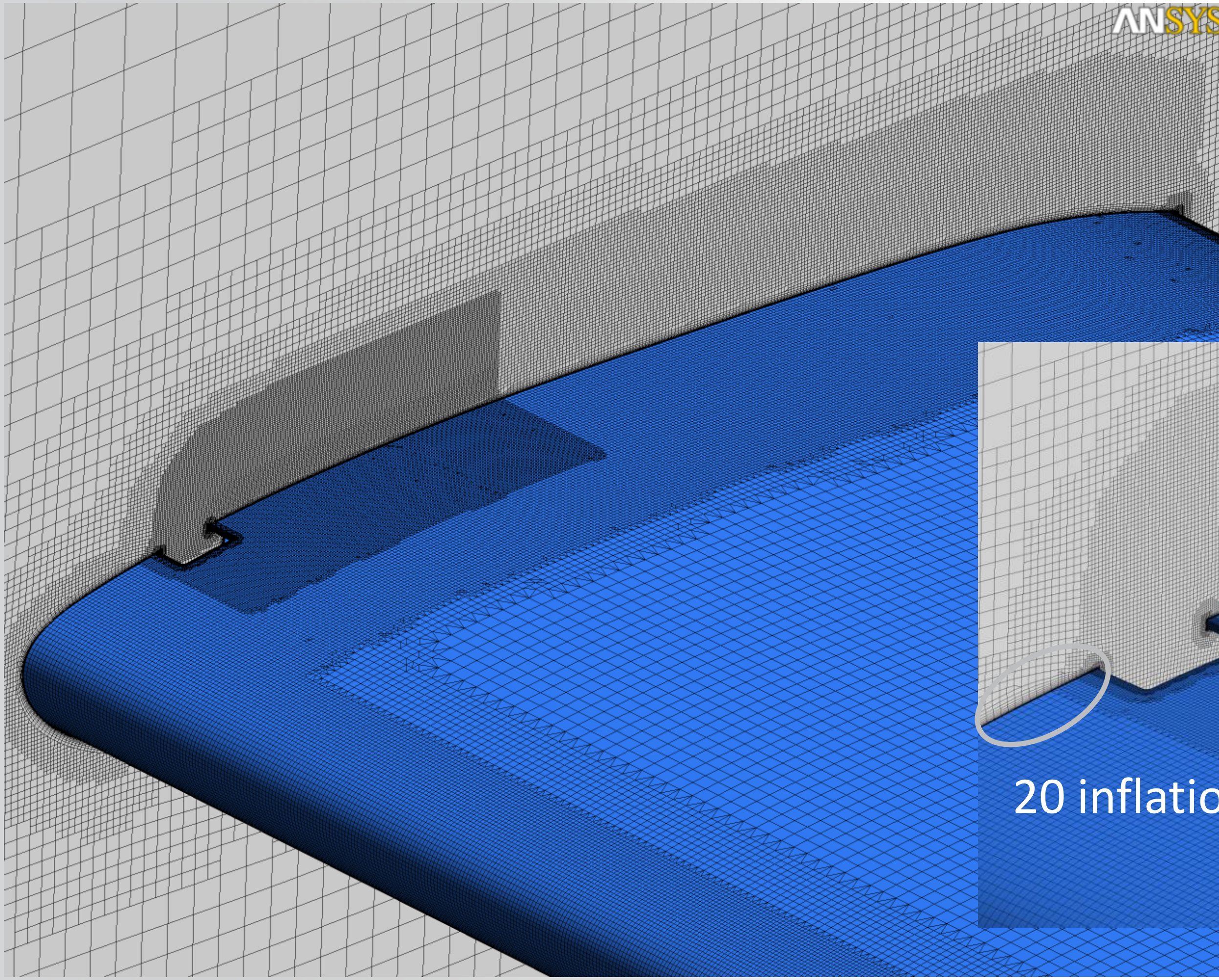
21,000,000 Elements
Min angle = 20.0°
Max AR = 7,600
Max VC = 8



Courtesy: Benjamin Duda, Airbus Toulouse

ANSYS

Hybrid Cartesian Mesh



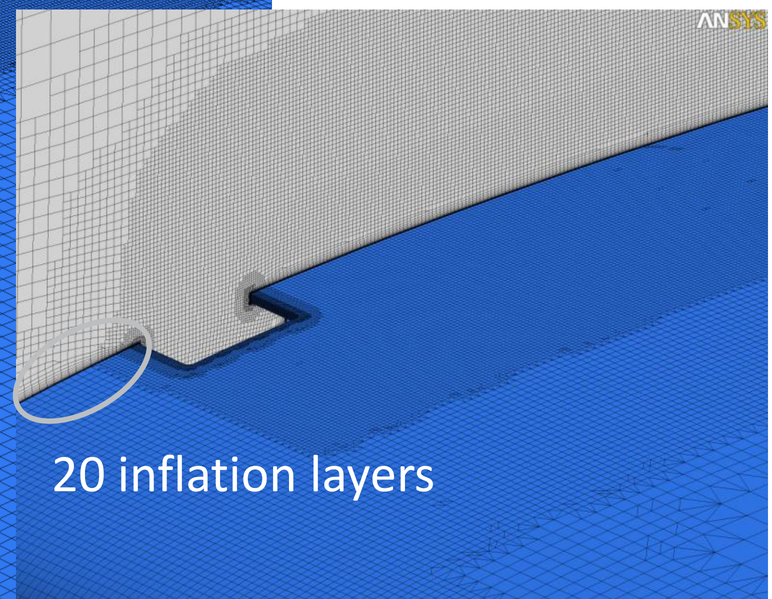
13,100,000 Elements

Min angle = 6.0°

→ 30 Elements < 15°

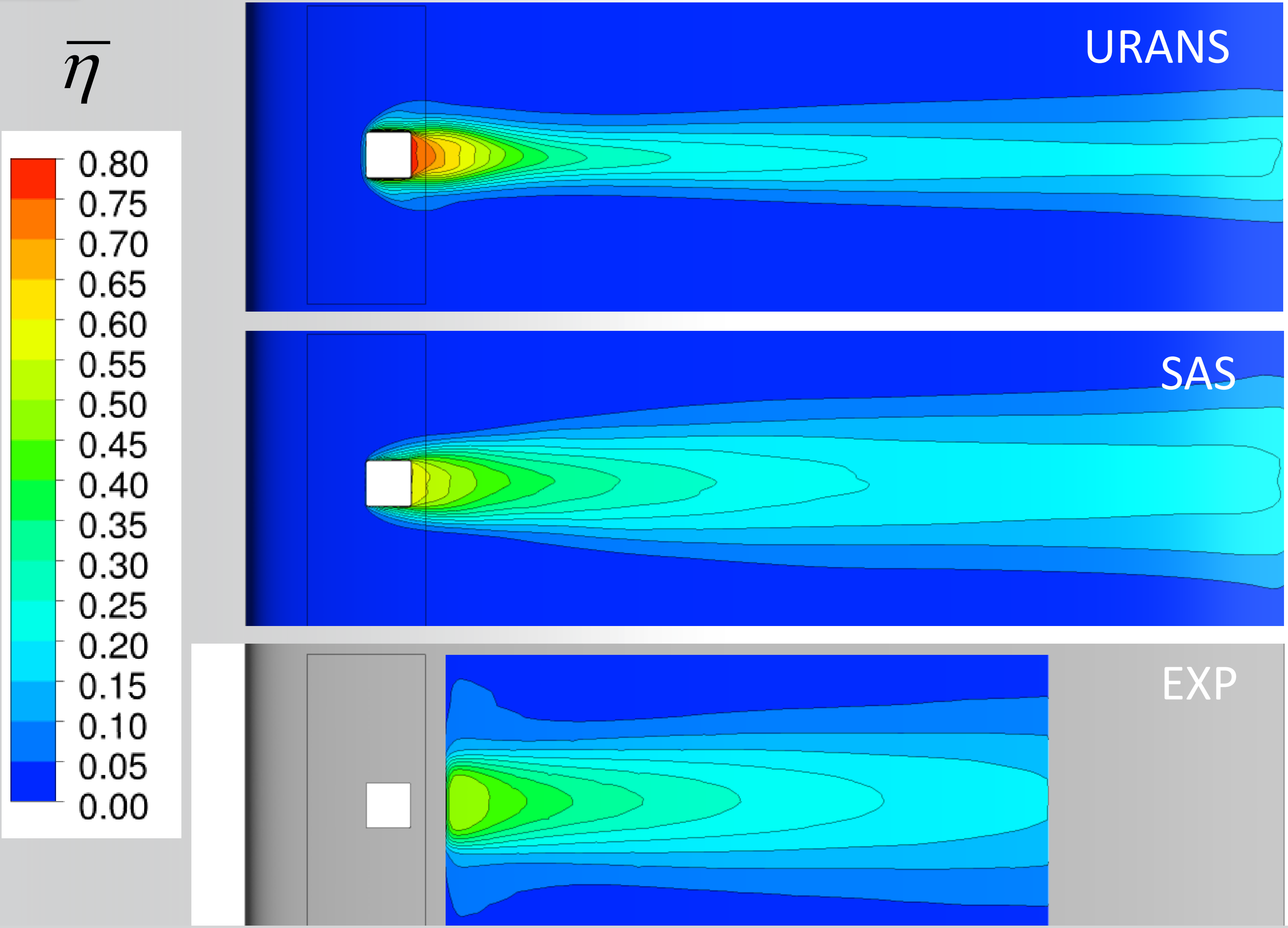
Max AR = 6,000

Max VC = 16



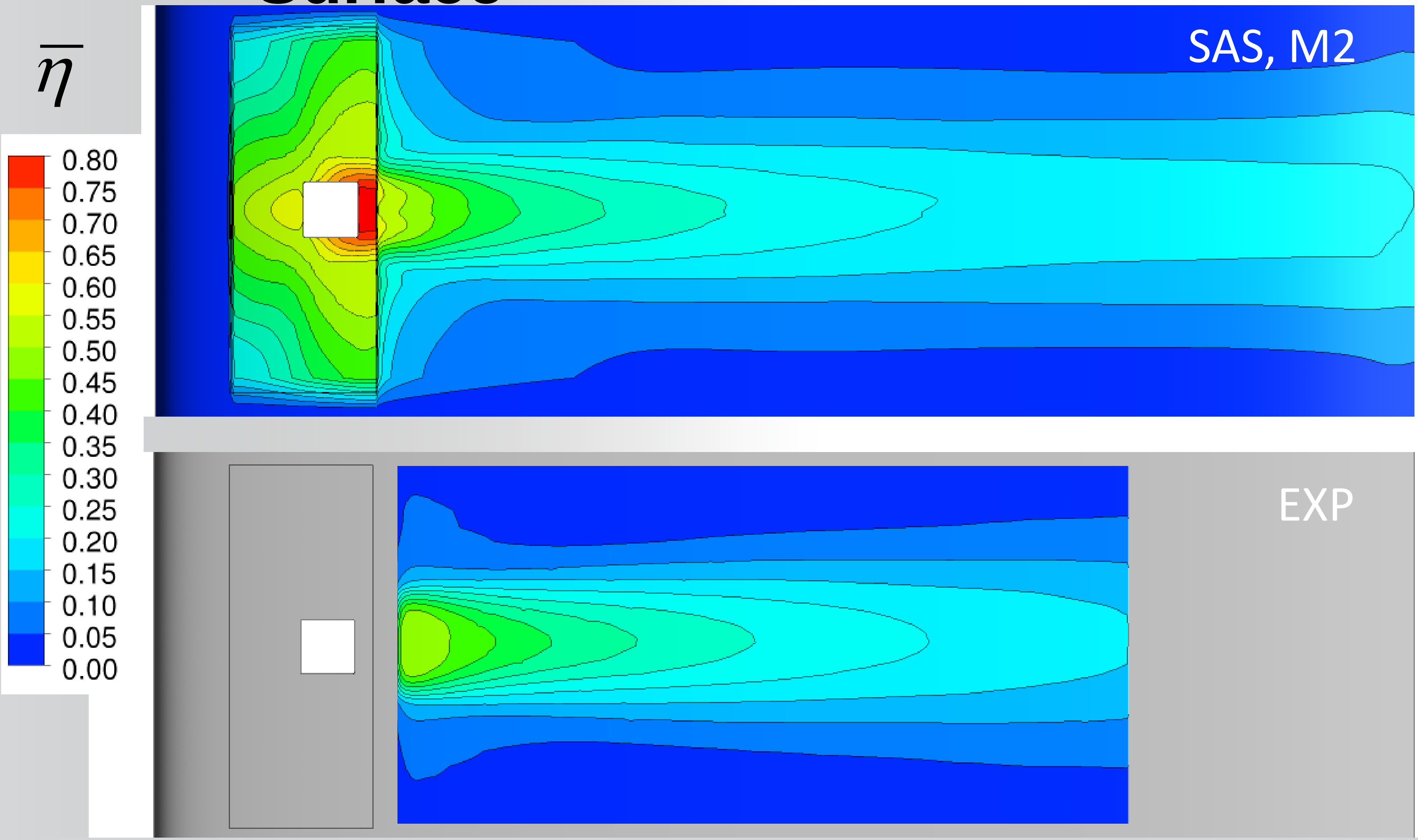
Courtesy: Benjamin Duda, Airbus Toulouse

Mean Thermal Efficiency on Wing Surface



Courtesy: Benjamin Duda, Airbus Toulouse

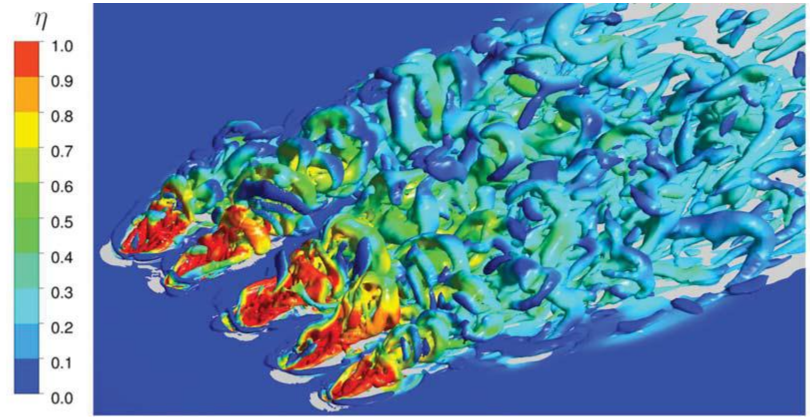
Mean Thermal Efficiency on Wing Surface

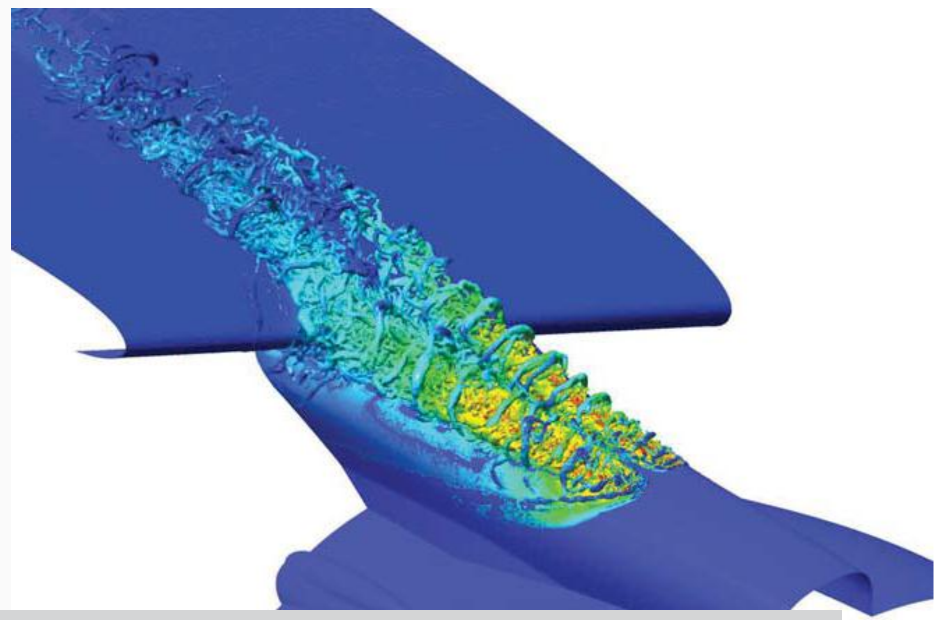


Courtesy: Benjamin Duda, Airbus Toulouse

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





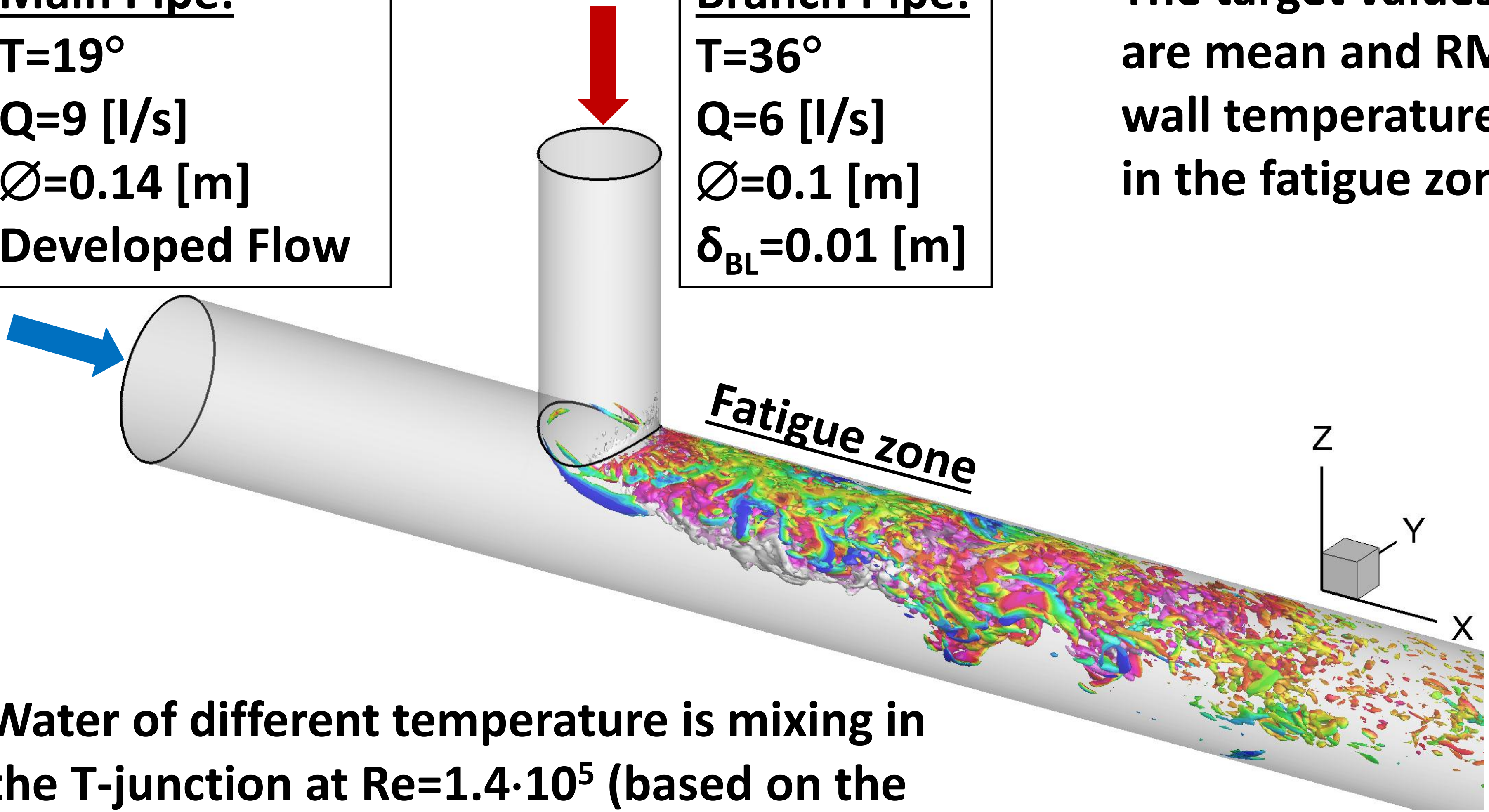
Courtesy: Benjamin Duda, Airbus Toulouse

Flow schematic

Main Pipe:
T=19°
Q=9 [l/s]
∅=0.14 [m]
Developed Flow

Branch Pipe:
T=36°
Q=6 [l/s]
∅=0.1 [m]
δ_{BL}=0.01 [m]

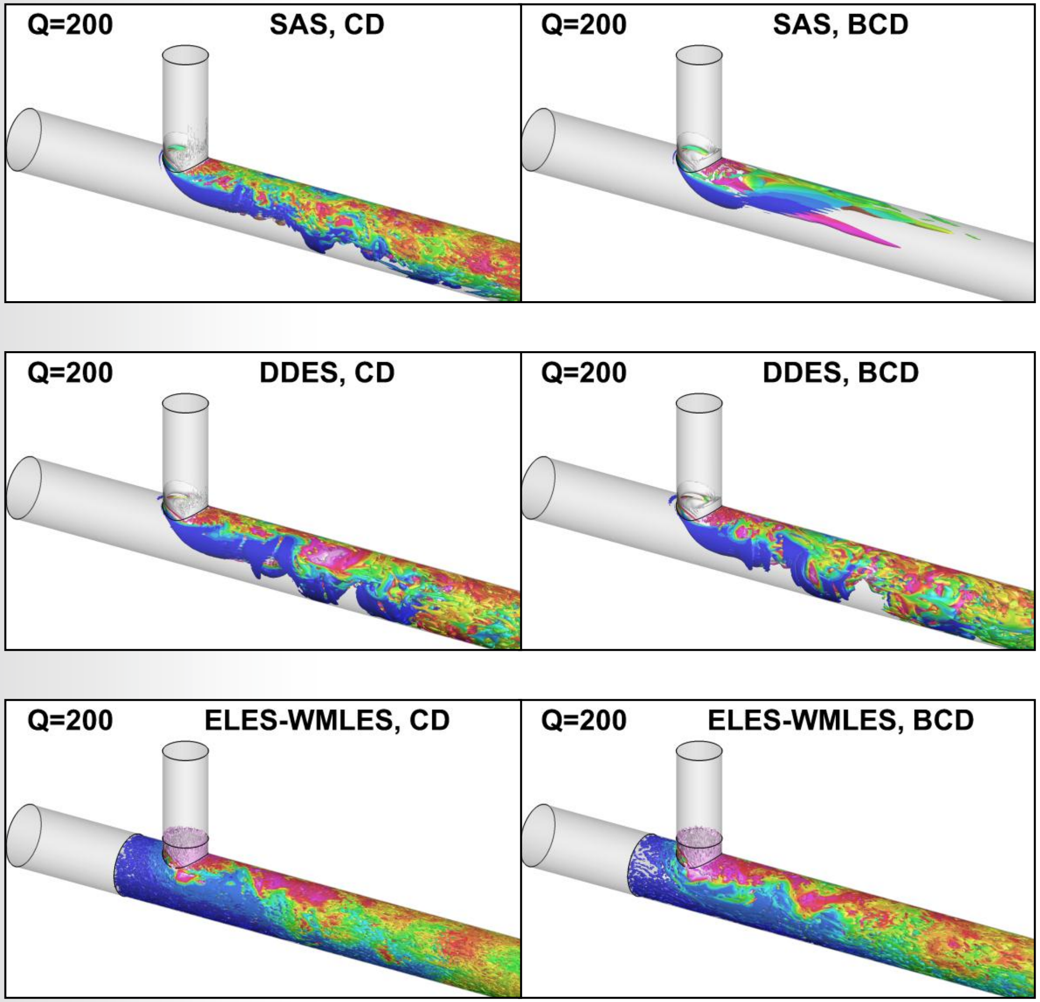
The target values are mean and RMS wall temperatures in the fatigue zone



Water of different temperature is mixing in the T-junction at Re=1.4·10^5 (based on the main pipe bulk velocity and on its diameter)

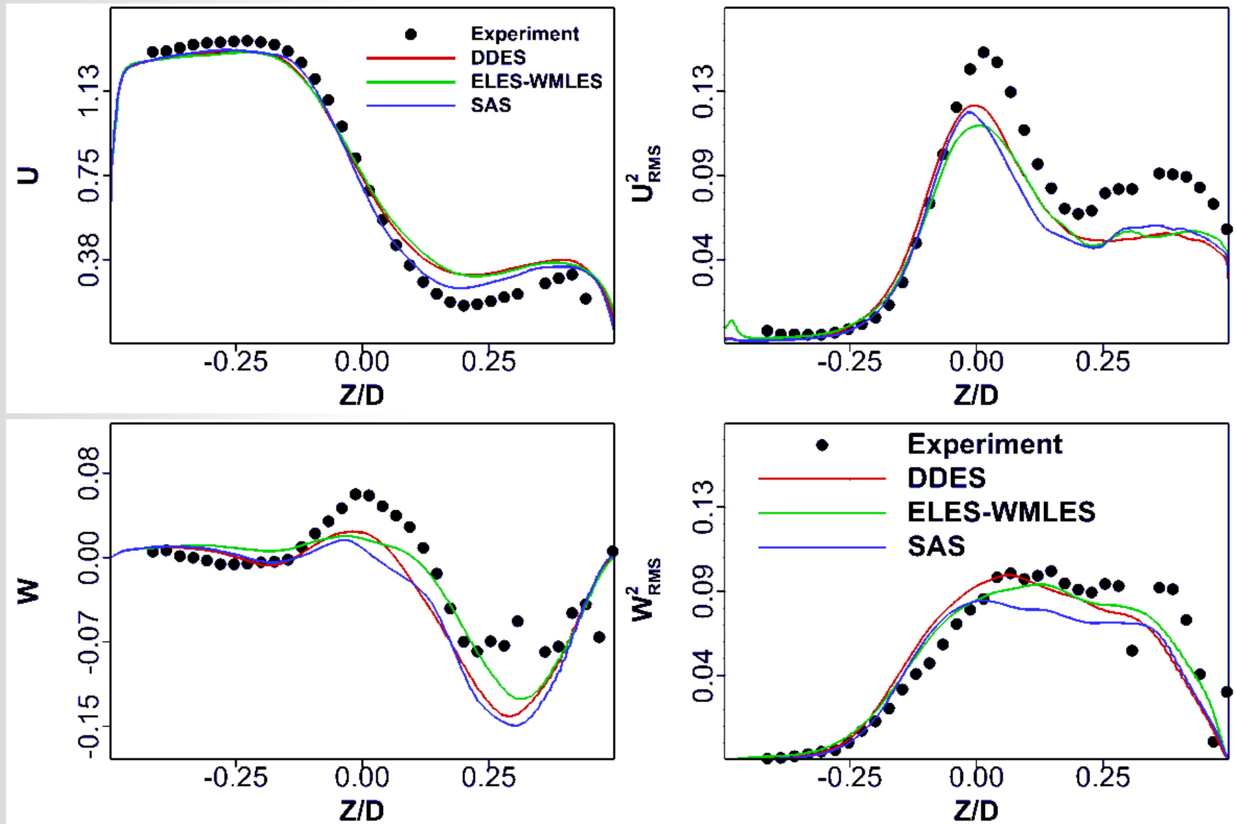
Isosurfaces of Q-criterion Colored with Temperature for Different SRS Models

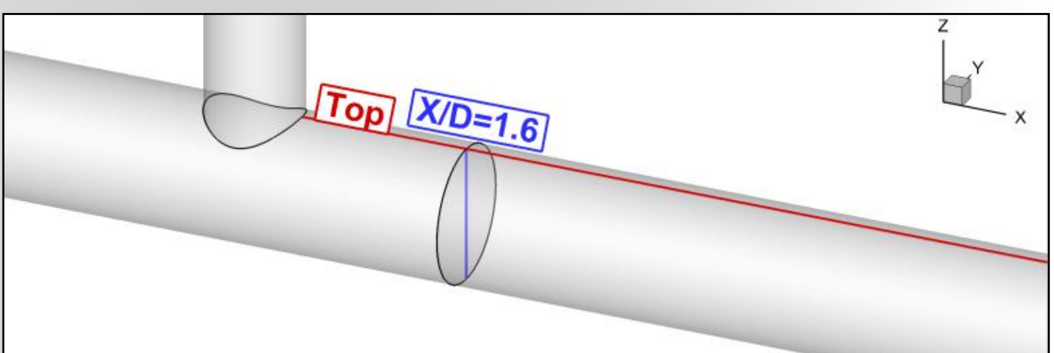
- Sensitivity to numerics depends on the SRS model
- SAS with BCD is virtually steady
- The reason is that the flow is not enough unstable
- Unsteady solution with resolved turbulent structures is obtained for the CD scheme
- For other models the effect of numerics is not seen from instantaneous fields



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

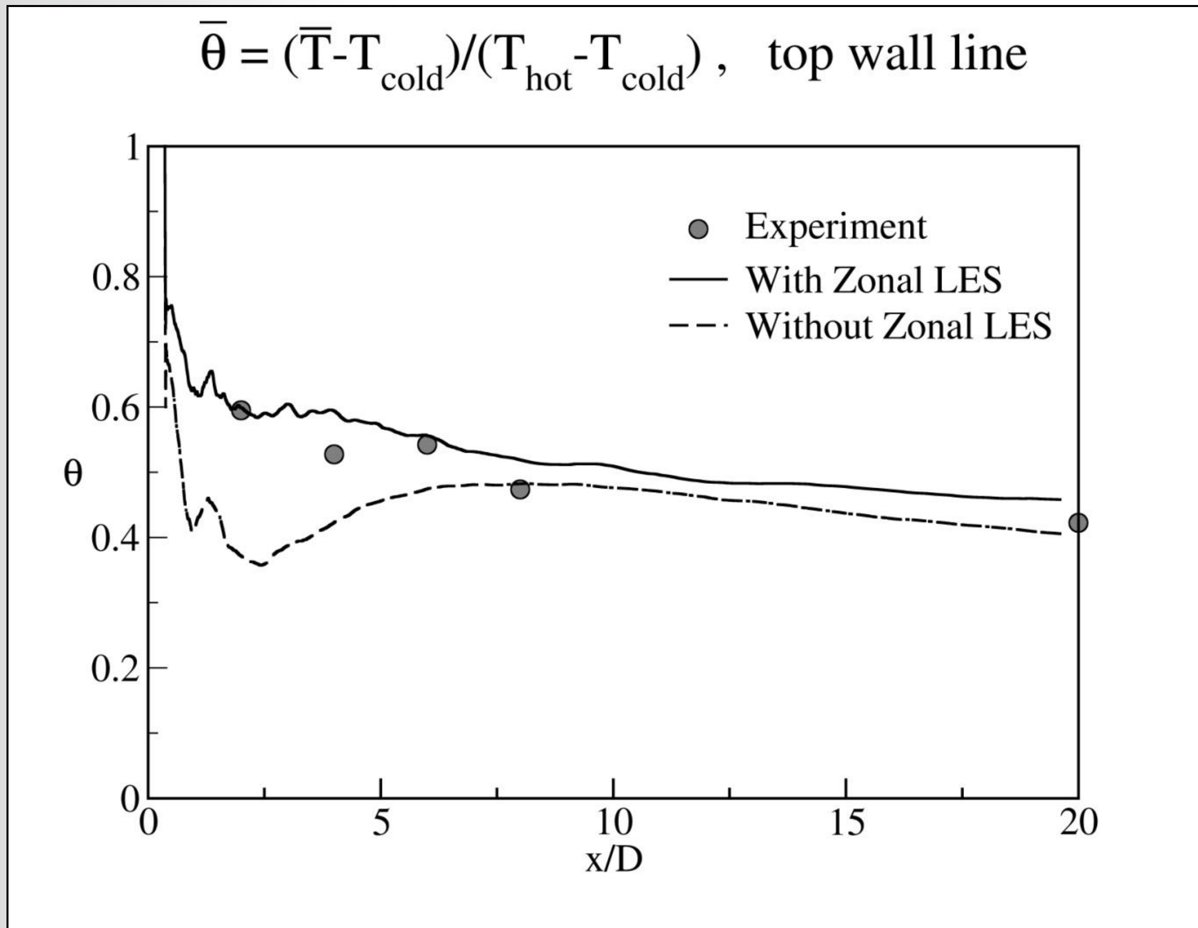




Influence of Zonal LES, weak BCD

Wall temperature in the fatigue zone

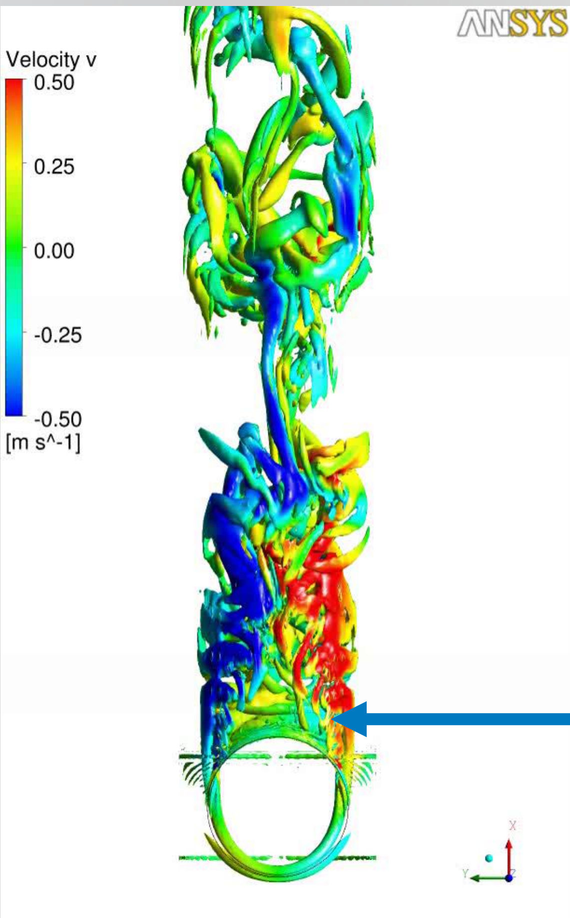
- Noticeable differences appear when looking at the wall temperature
- All global models failed to provide the correct temperature distribution right past the intersection
- Only zonal (embedded) formulation is able to provide the correct mixing already from the start of the mixing zone



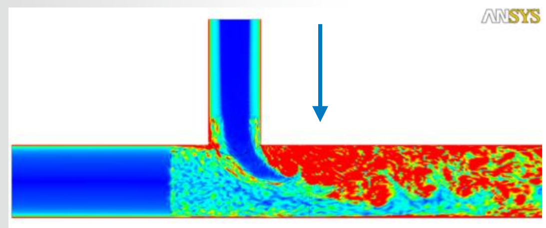
Influence of Zonal LES, weak BCD

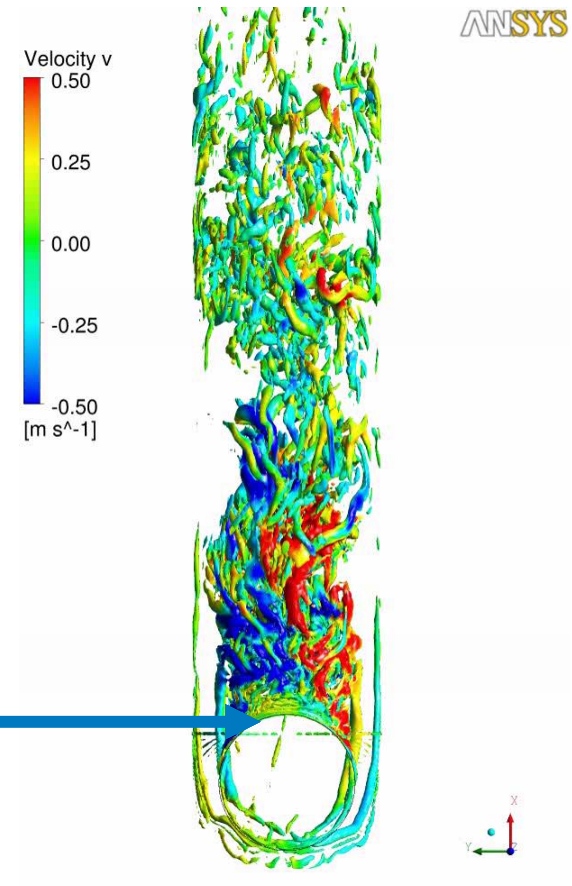
**With DDES,
Q=1000**

**With zonal LES,
Q=8000**



**View from
the top**

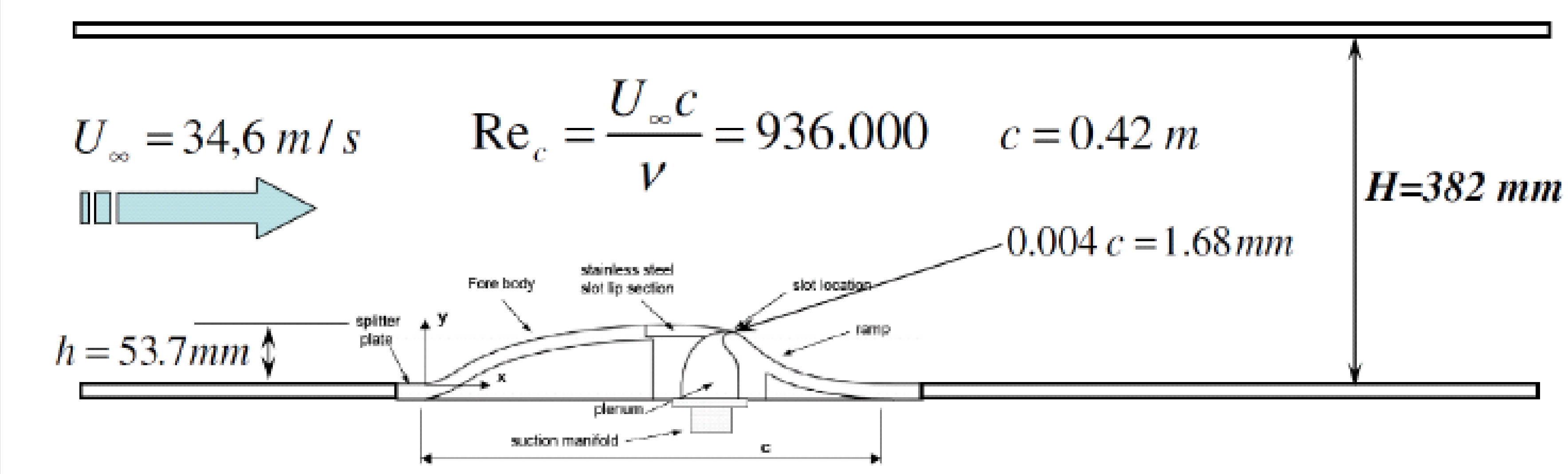




**Different mixing
pattern**

Flow over a wall mounted hump

Flow configuration:



Simulation: baseline (no flow control)

Testcase of EU Project ATAAC

http://cfd.mace.manchester.ac.uk/twiki/bin/view/ATAAC/WebHome

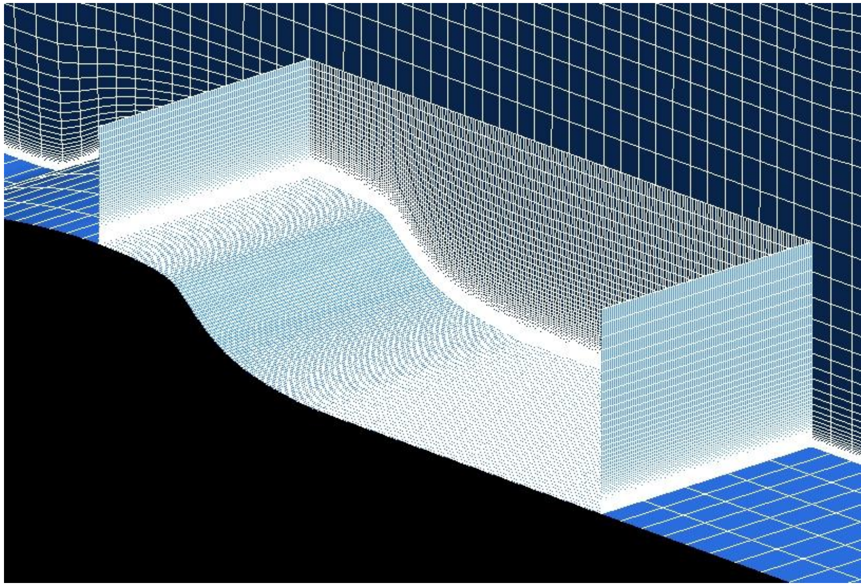
Flow over a wall mounted hump, Geometry and Grid

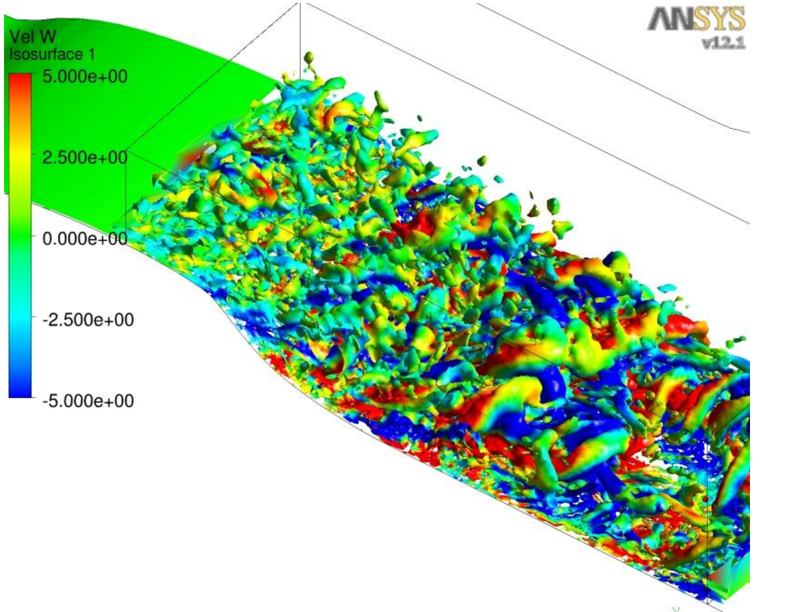
Geometry:

- Spanwise extent:
  - 3.16 H (bump height)
  - 5.6 $\delta_{interface}$ (δ – boundary layer thickness).

Grid:

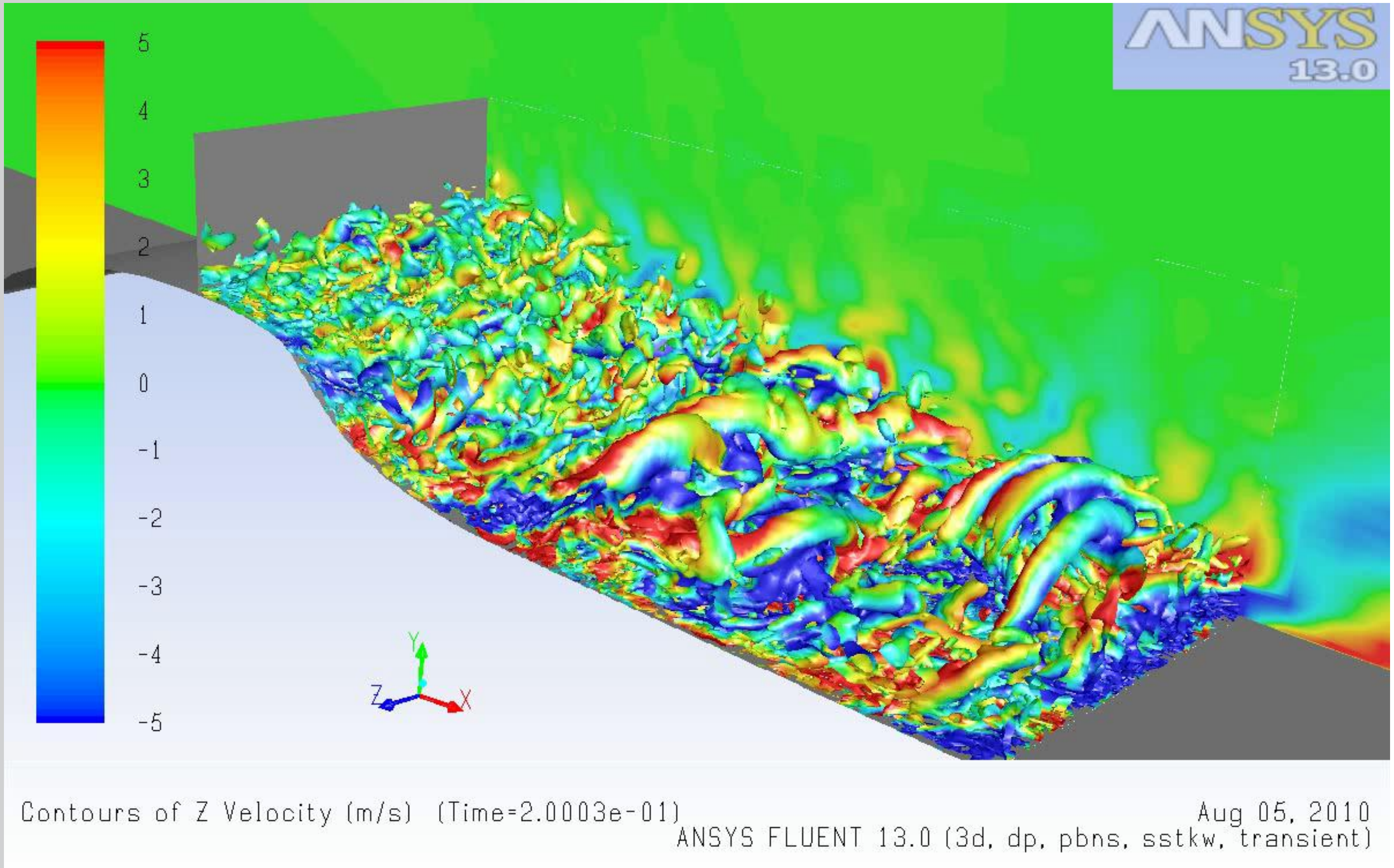
- RANS grid with only 5 cells in spanwise direction
- LES grid: 200x100x100 (2 million)
- Grid resolution per inlet boundary layer ($\Delta x/\delta$=10, $\Delta z/\delta$~20, NY~40.





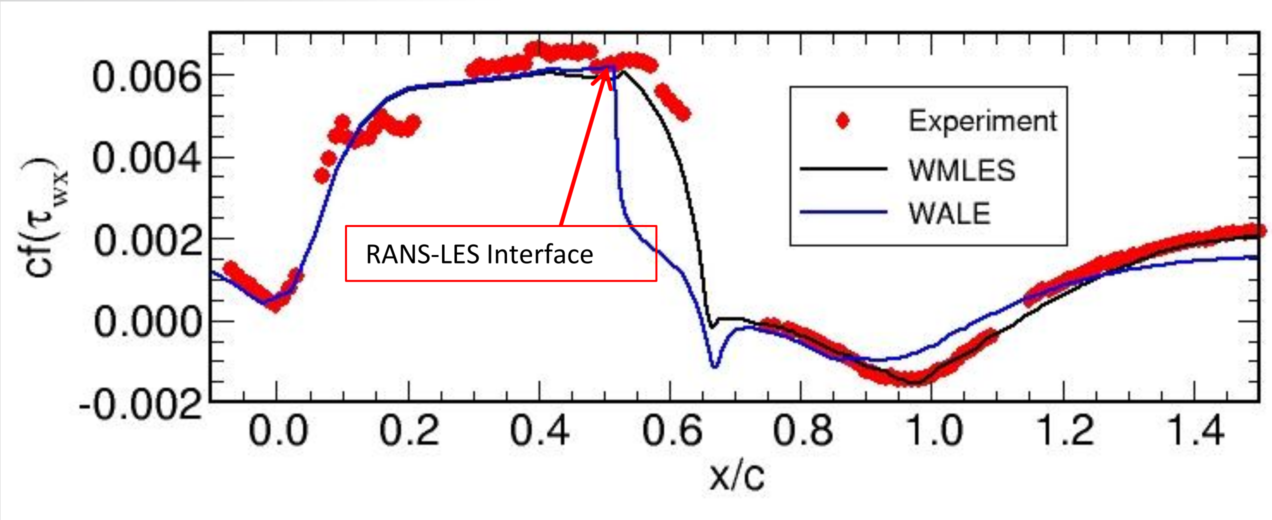
Flow over a wall mounted hump

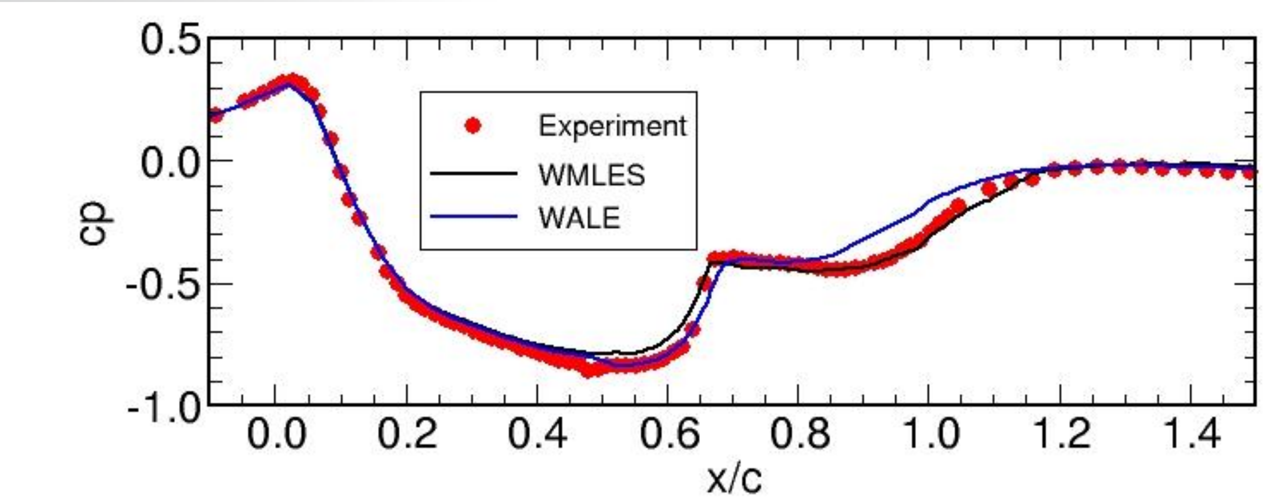
Q criterion:



Flow over a wall mounted hump Wall Shear Stress and Wall Pressure

- The Re number at the RANS-LES interface is Re_{Θ}=7000
- If the simulation in the LES region is carried out with a standard LES model (WALE) the solution is lost immediately after the interface
- The WMLES formulation is able to carry the solution smoothly across and provide a good agreement with the data for two different time steps (CFL~0.5 and CFL~0.12)

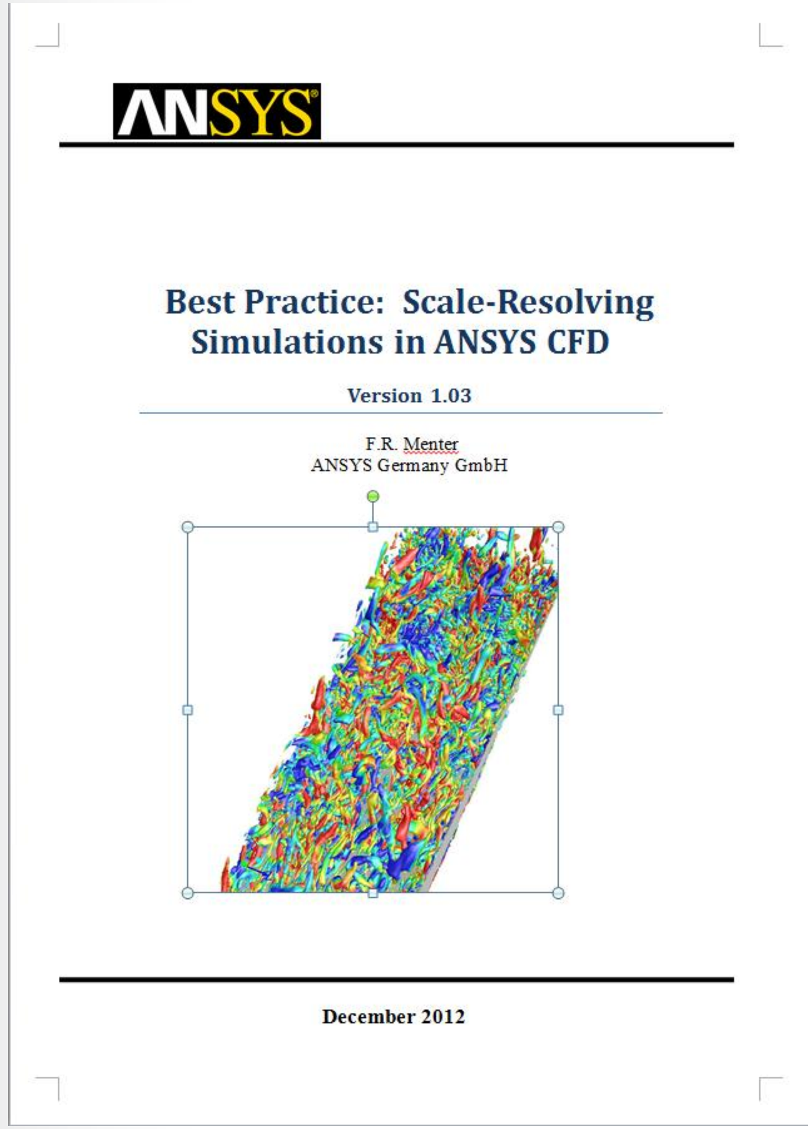




Overall Summary

- RANS modelling key to industrial CFD
  - Grid quality is key issue
- Transition modelling important for many applications
  - Turbomachinery
  - Wind turbines
  - …
- SRS is making its way into industrial CFD
- Different types of model recommended for different types of applications
- Currently favored methods within ANSYS software:
  - SAS – globally unstable flows
  - DDES – globally and locally unstable flows
  - ELES/WMLES marginally unstable flows

Best Practice


Best Practice: Scale-Resolving Simulations in ANSYS CFD

Version 1.03

F.R. Menter
ANSYS Germany GmbH

December 2012