NASA/CP—2010-216112

Institut für Thermische Strömungsmaschinen
Prof. Dr.-Ing. H.-J. Bauer

DNS and Embedded DNS as Tools for Investigating Unsteady Heat Transfer Phenomena in Turbines

Dominic von Terzi

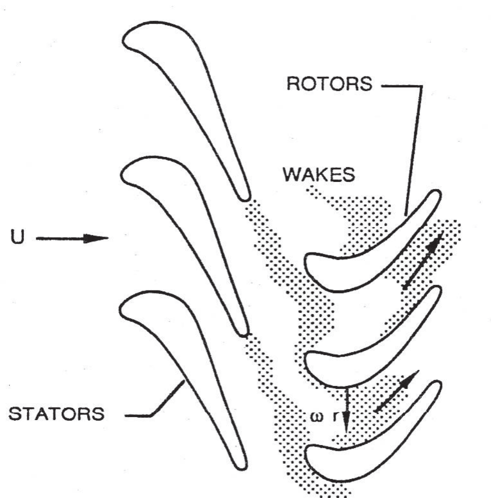
Collaborators:
Lars Venema, Hayder Schneider, Wolfgang Rodi, Hans-Jörg Bauer

Universität Karlsruhe (TH)
Forschungsuniversität • gegründet 1825

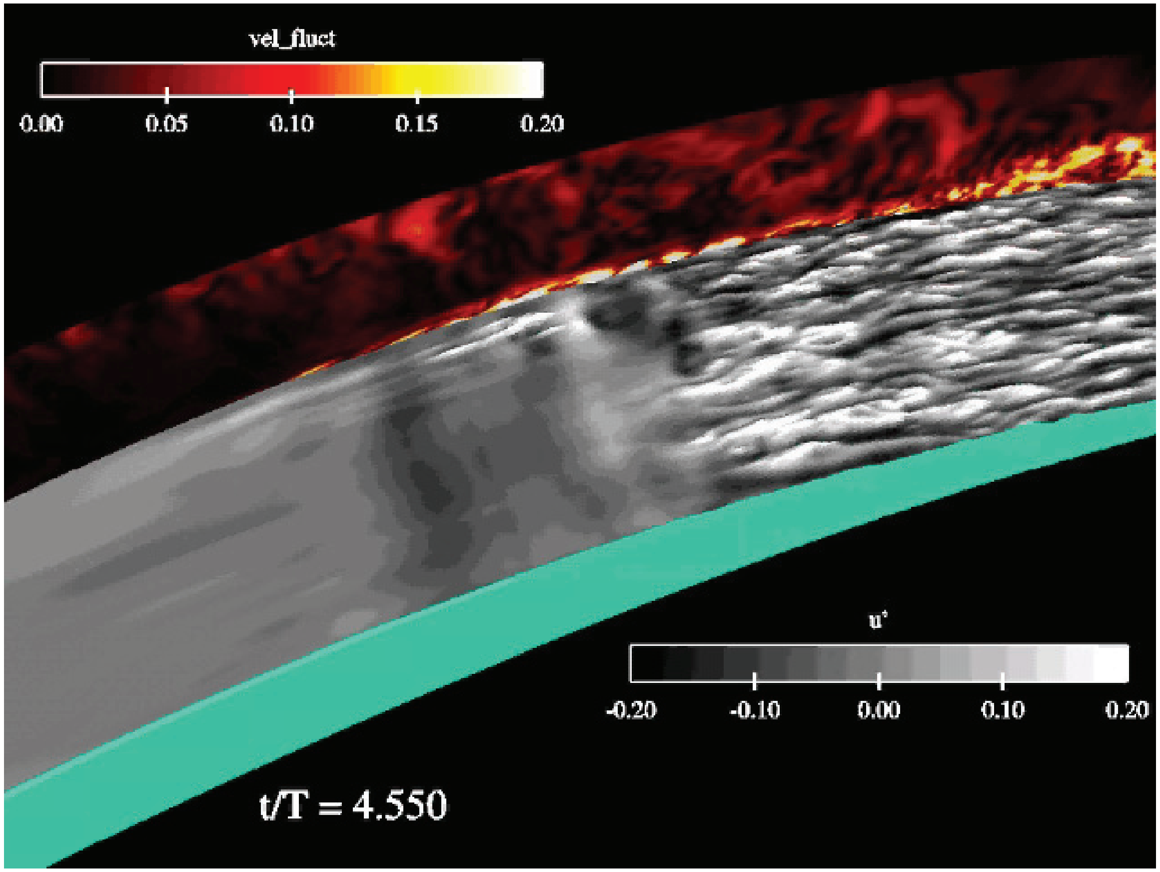
Classical DNS for Turbomachinery

Laminar-turbulent transition of a boundary layer on a compressor blade:

Development of turbulence in the boundary layer is accelerated by wakes of the approach flow



u-fluctuations
Red: Wakes
Gray: Boundary layer (turbulent spots)



Rodi *et al.* (2007)

Click to play animation

filename: 03V103X_ufluc_ss.avi

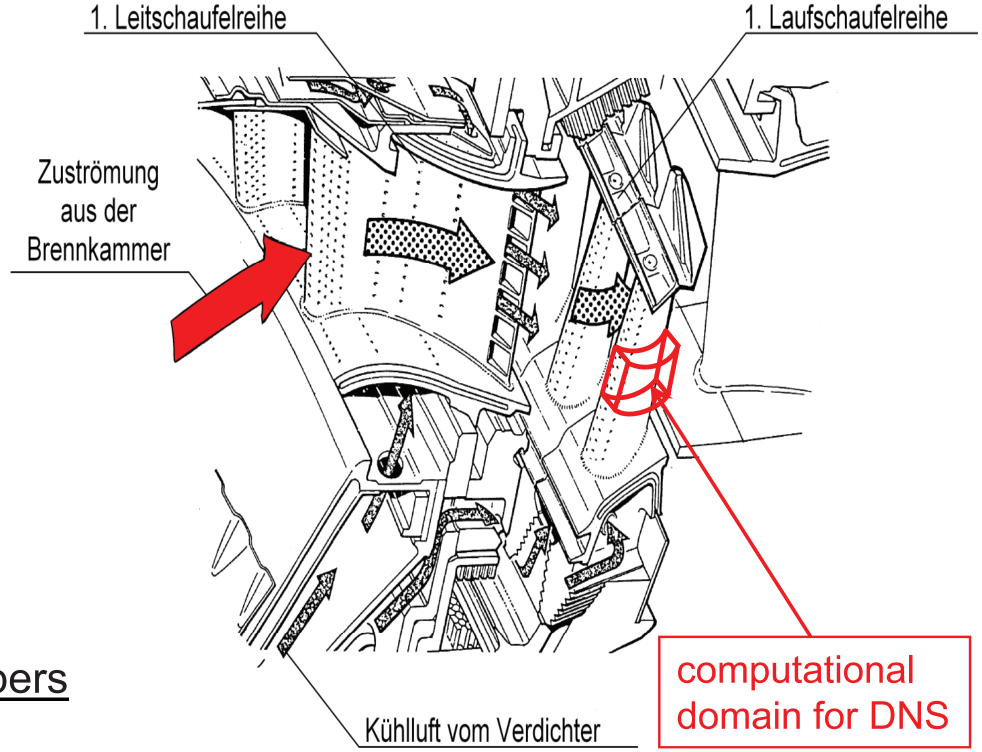
Drawbacks of classical DNS

Demands on computer resources are extremely high!

Computational costs of some examples:

- Turbine blade (Wissink & Rodi, 2006):
  93.4 million cells
  240 000 time steps
  512 000 CPU-hours on
  Hitachi SR8000-F1
  ca. 3 months on 256 CPUs
- Compressor blade (Rodi *et al.*, 2007):
  85 million cells
  256 000 time steps
  31 000 CPU-hours on NEC SX-8
  ca. 20 days on 64 CPUs

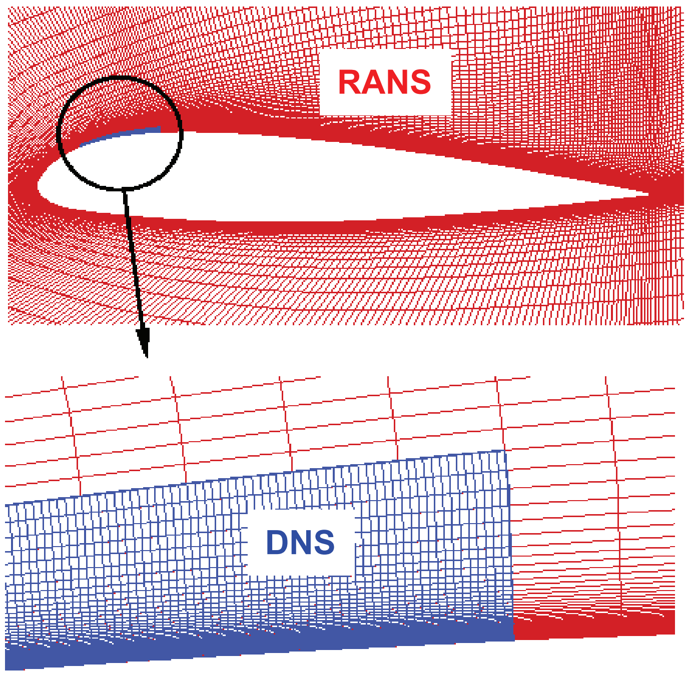
⇒ So far only idealized configurations,
small domains and low Reynolds numbers



Proposed remedy: Development of an “**embedded DNS**“ method
(DNS domain enclosed in RANS / LES domains)

The case for "embedded DNS"

Illustration: DNS-zone embedded in RANS-domain for better prediction of laminar-turbulent transition of the flow over an airfoil



Advantage:

RANS on coarser 2D grid, fine 3D grid for **DNS only in small sub-domain**

⇒ Immense reduction in computational cost

Required development of new technique:

Different **demands on numerical methods** in RANS and DNS areas

⇒ Adjustment of the flow solver

Key problem: Coupling at **interfaces**

⇒ Physically meaningful fluctuations required for DNS-boundaries (RANS delivers only mean values and LES only large-scale fluctuations!)

→ **Can learn from suitable hybrid LES/RANS methods**

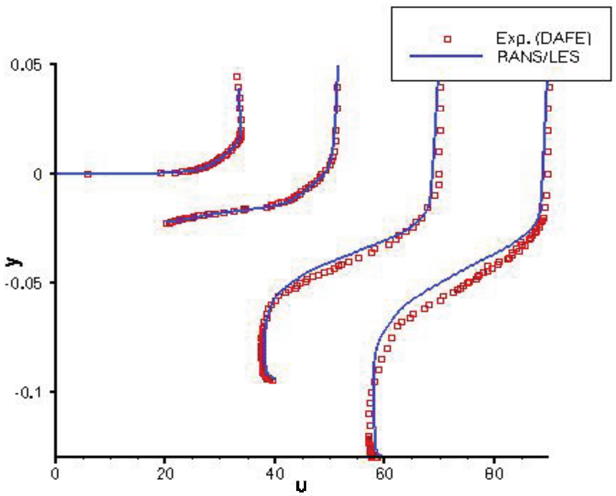
von Terzi & Fröhlich (TSFP-5 2007, ETMM-7 2008), review: Fröhlich & von Terzi (JPAS, 2008)

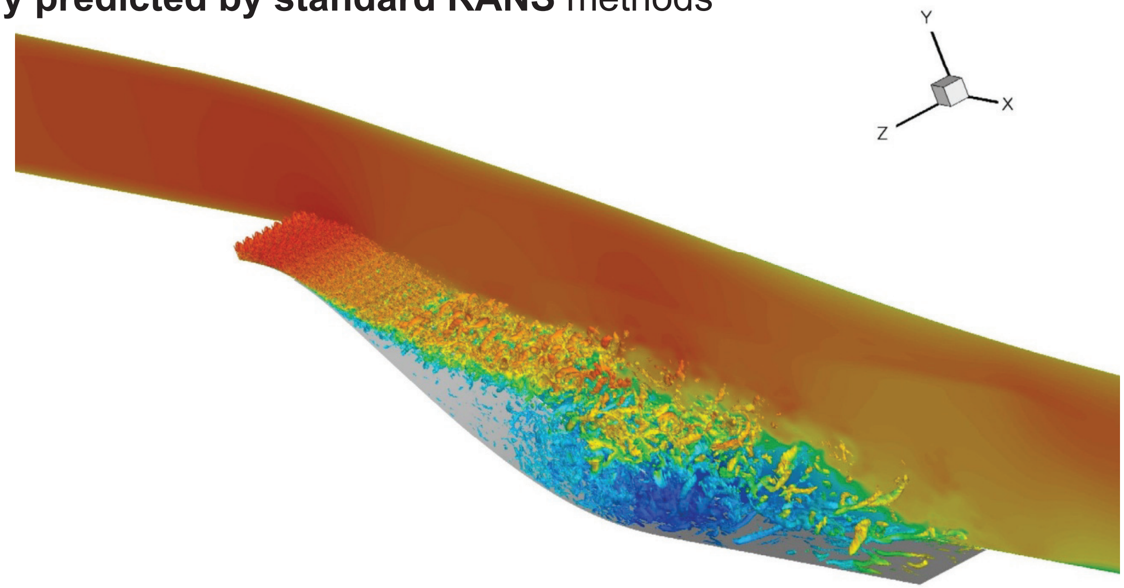
Illustrating example: Embedded LES

Separated flow in an asymmetric air intake:

Dilemma: Approach boundary layer at high Reynolds number **too costly for LES**, whereas separated flow region **poorly predicted by standard RANS** methods

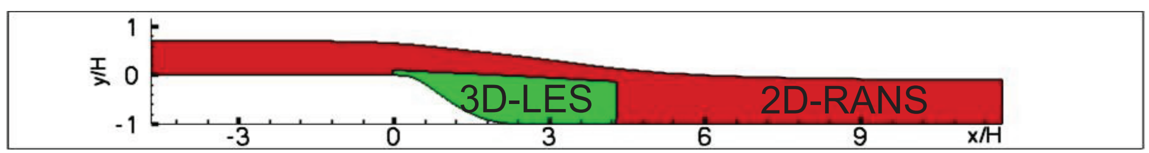
Re=400,000; 9.2 million cells





Vortex identification by Q-criterion

Generation of fluctuations:
- inflow: database
- other boundaries: enrichment



courtesy of I. Mary, ONERA (see also v. Terzi, Fröhlich & Mary, inSiDE 2009)

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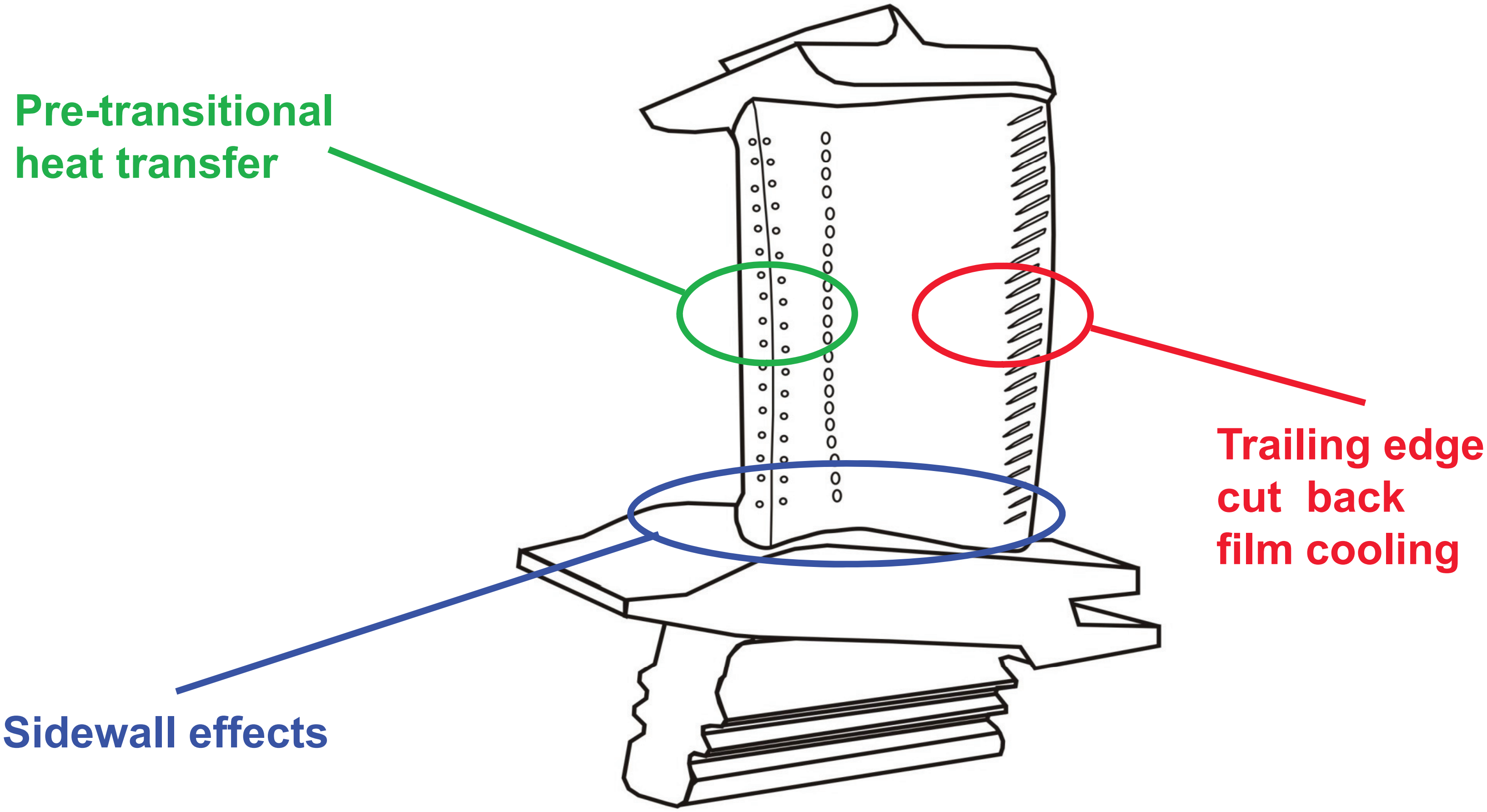
Candidates for (embedded) DNS studies in turbines

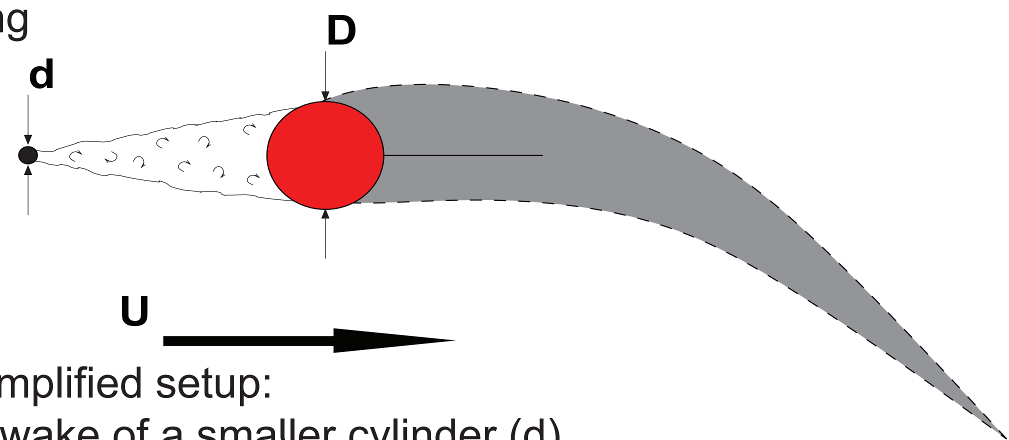


Mid-term goal: integrate in a complete turbine blade simulation with embedded DNS

Project: Pre-transitional heat transfer

with Venema & Rodi

Motivation:
- Increase in heat transfer at stagnation point of turbine blades due to incoming wakes and turbulence
- Physical mechanism unclear
- Predictions with RANS inaccurate and not reliable



First step:
Reproduce experimental results for a simplified setup:
A larger cylinder (D) is immersed in the wake of a smaller cylinder (d)
Re_D=48,000 (Magari & LaGraff, *J. Turbomachinery* 1994)

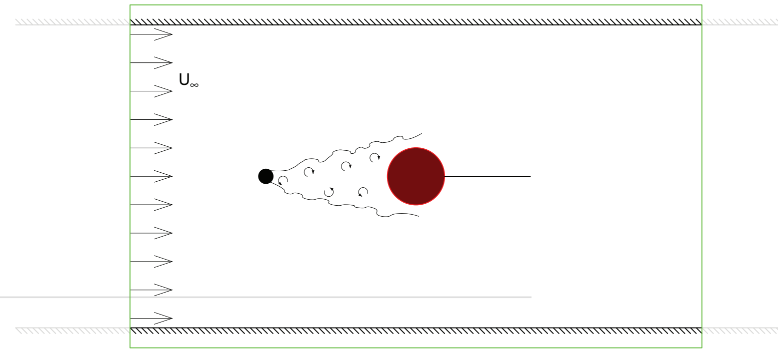
Second step:
Reproduce selected experimental results for a turbine blade

Third step:
Own numerical experiments to understand mechanism
→ better prediction of heat transfer

Project: Pre-transitional heat transfer

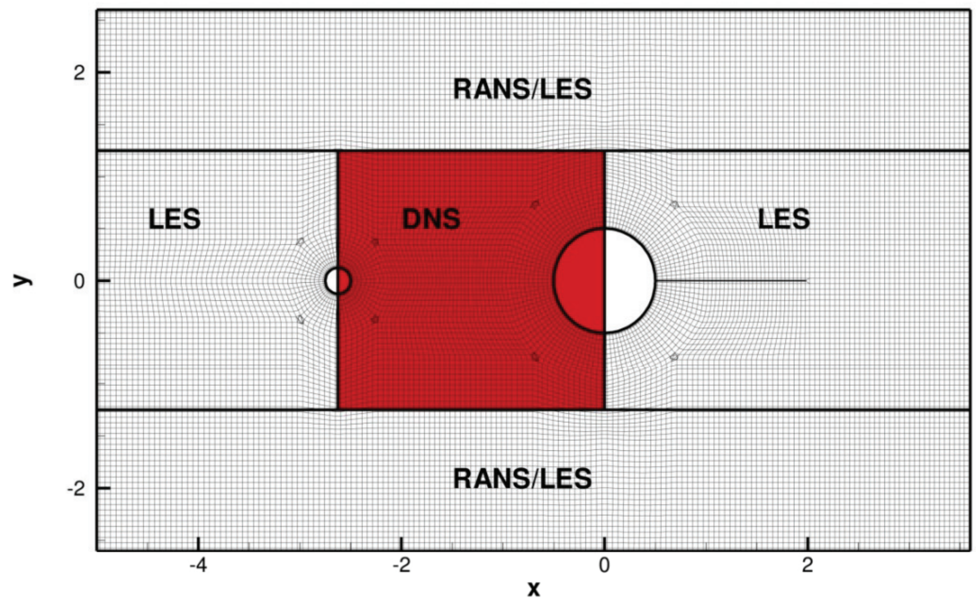
with Venema & Rodi

Schematic of setup for embedded DNS



Preliminary simulations:
Re_D=48,000; 2 domain widths (2.5D & 1D);
each ca. 40 million cells, almost all in DNS region (in red)

Final simulations:
Estimated 200 & 800 million cells



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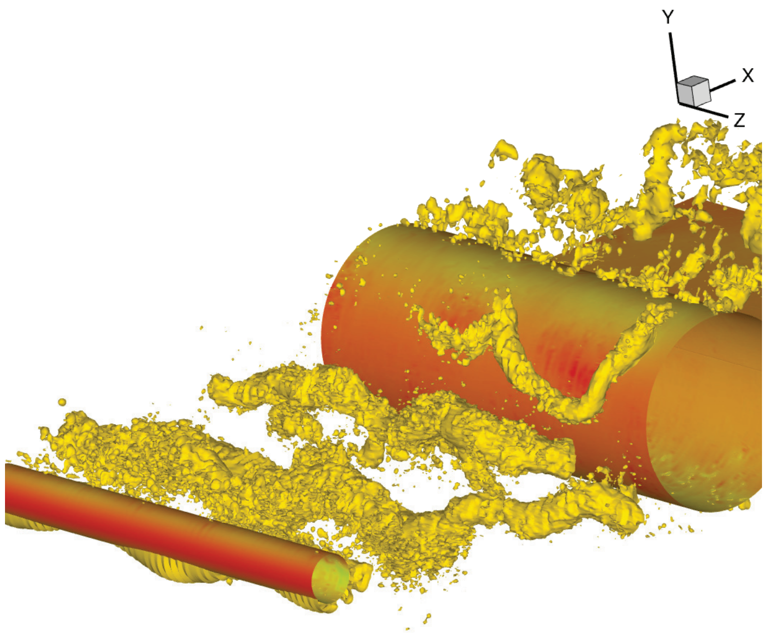
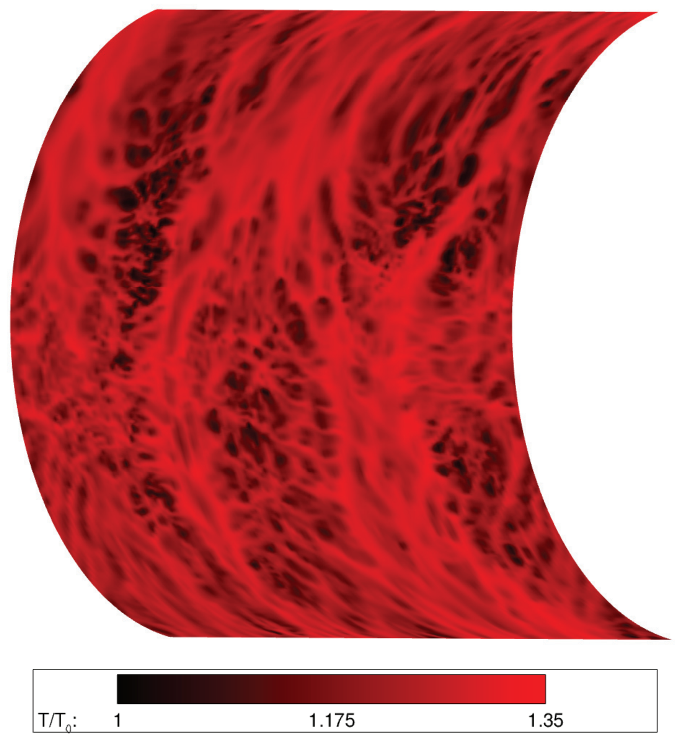
Preliminary DNS results: wake induced temperature fluctuations





Iso-contours of instantaneous **pressure fluctuations** and **temperature** at cells adjacent to cylinders (full domain width of experiments 2.5 D)

Instantaneous **temperature** contours at stagnation point of large (heated) cylinder (higher resolution, but narrower domain width)

Click to play animation

filename: 03T_bc_re48000_3d_mjpeg.avi

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Project: Pre-transitional heat transfer

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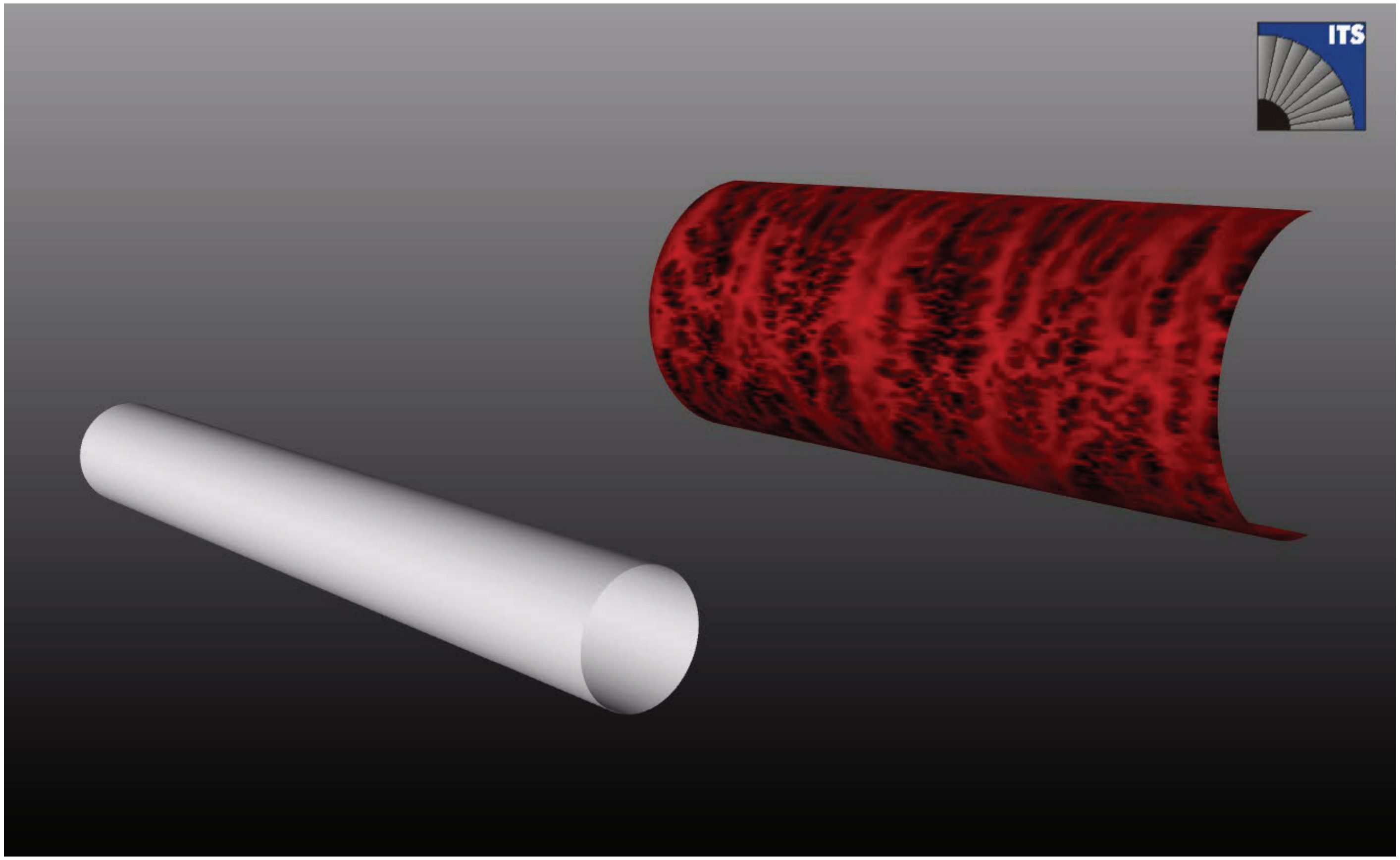
Instantaneous temperature contours (wall-adjacent cell at large heated cylinder)



Coarse simulation of full domain width

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Click to play animation

filename: 03dc_temp_rot.avi

Project: Trailing-edge cutback film-cooling

with Schneider & Bauer

Motivation:

Cooling film degradation due to enhanced mixing, presumably caused by large coherent structures, but exact mechanism unclear (competing mechanisms that can be exploited by flow control ?)

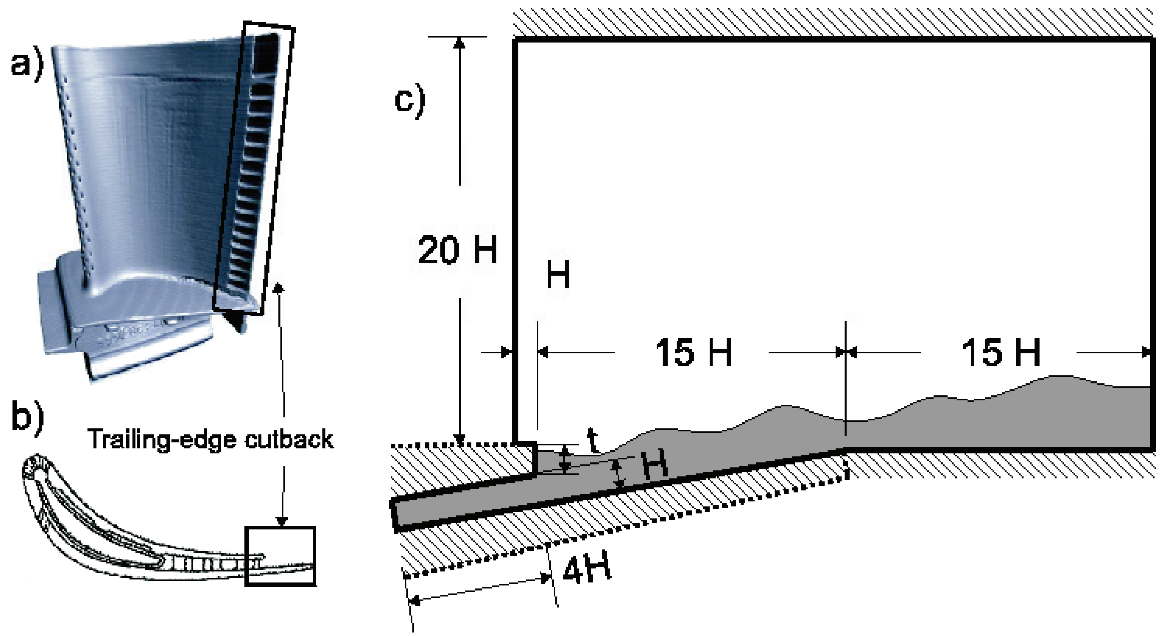
Focus here: IMPACT OF LOW BLOWING RATIO AND STATE OF COOLANT FLOW

Re_H=6,250

T_c/T_h=0.75

2 blowing ratios selected: M=0.5 & 1.1 (but velocity ratio matched !)

fully developed turbulent & laminar coolant flows simulated



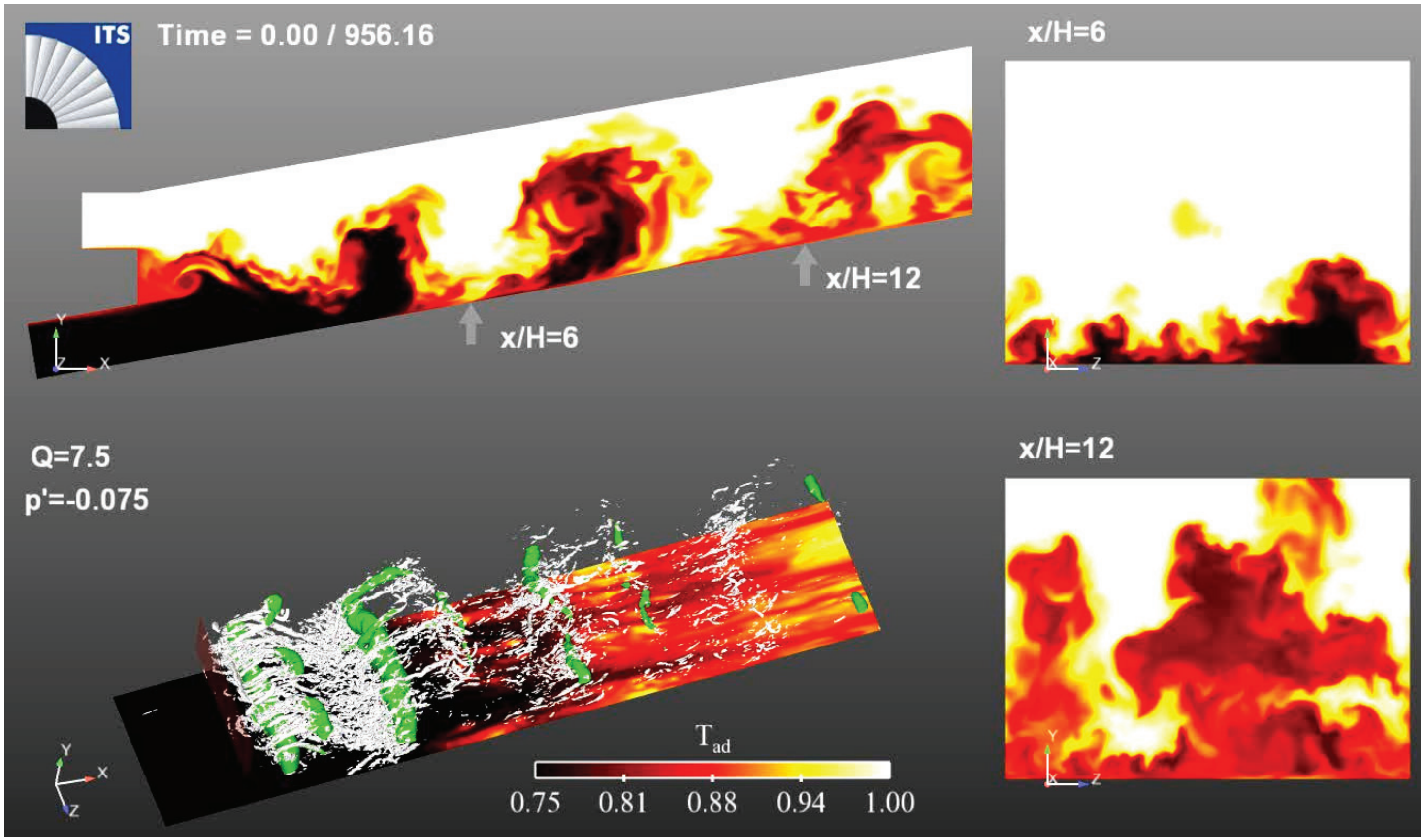
Experiments of AITEB-1/2 by Martini, Schulz & Bauer (J. Turbomachinery 2006) and Martini (2008)

Preliminary “LES” study (ca. 14 million cells, incompressible) with vanishing model contribution Schneider, v. Terzi & Bauer (THMT-6 2009)

Project: Trailing-edge cutback film-cooling

with Schneider & Bauer

Impact of coherent structures on the instantaneous flow and temperature field at the cutback for high **blowing ratio with turbulent coolant ejection**



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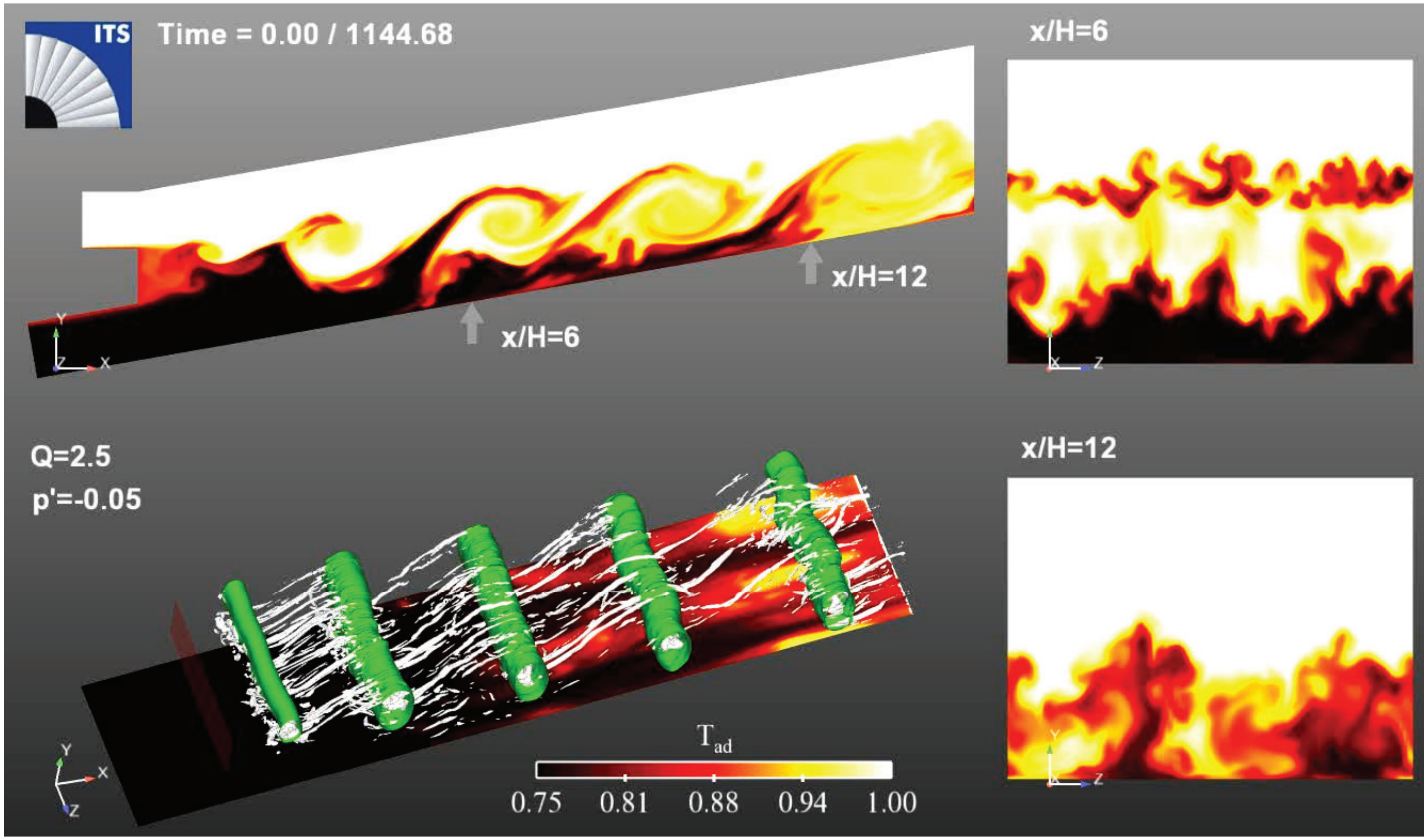
Click to play animation

filename: 03HK_LES_M1.1_run4_4views.avi

Project: Trailing-edge cutback film-cooling

with Schneider & Bauer

Impact of coherent structures on the instantaneous flow and temperature field at the cutback for **low** **blowing ratio with turbulent coolant ejection**



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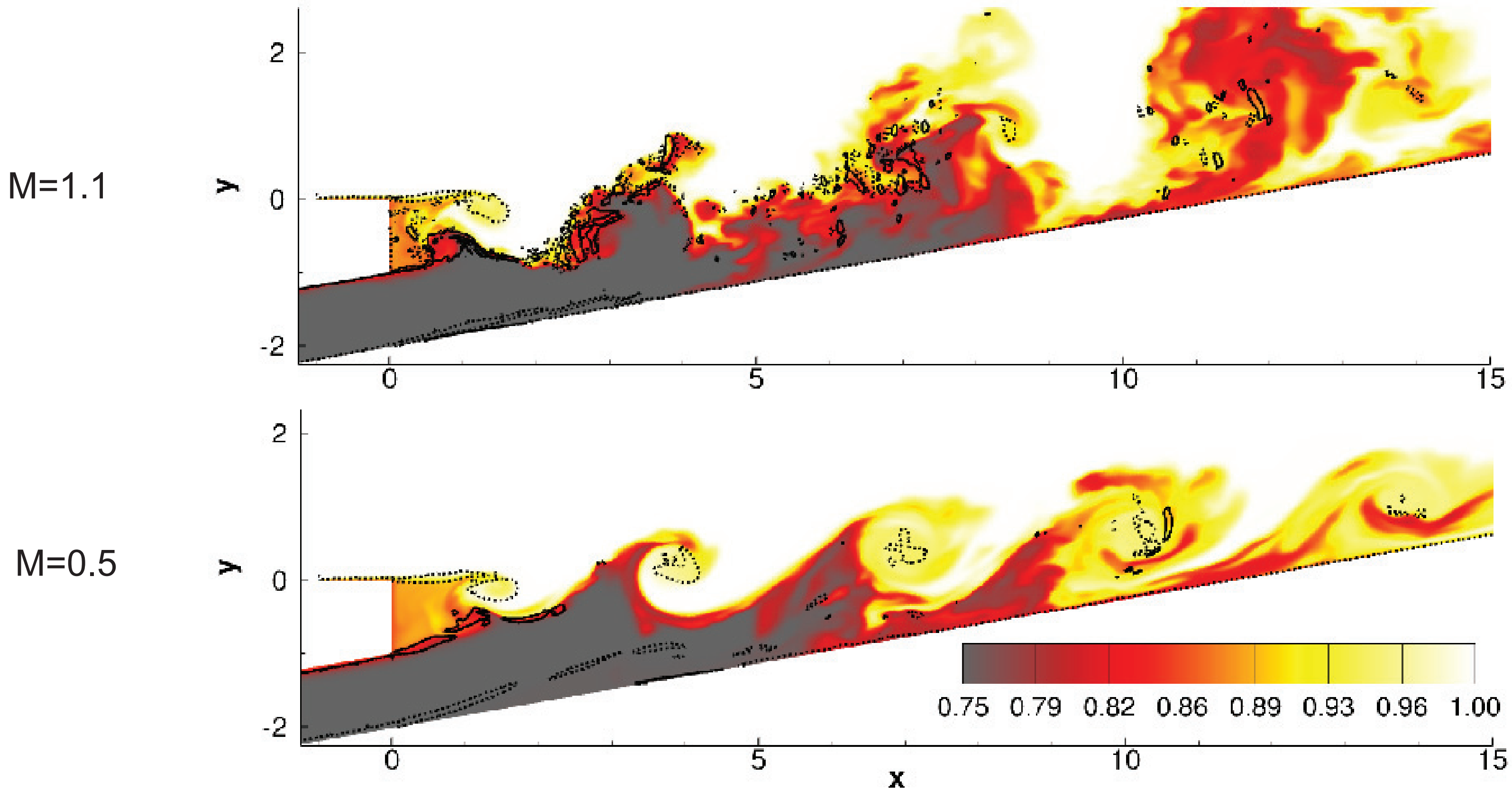
Click to play animation

filename: 03HK_LES_M0.5_run2_4views.avi

Project: Trailing-edge cutback film-cooling

with Schneider & Bauer

Difference in coherent structures for turbulent coolant cases (largest scales)



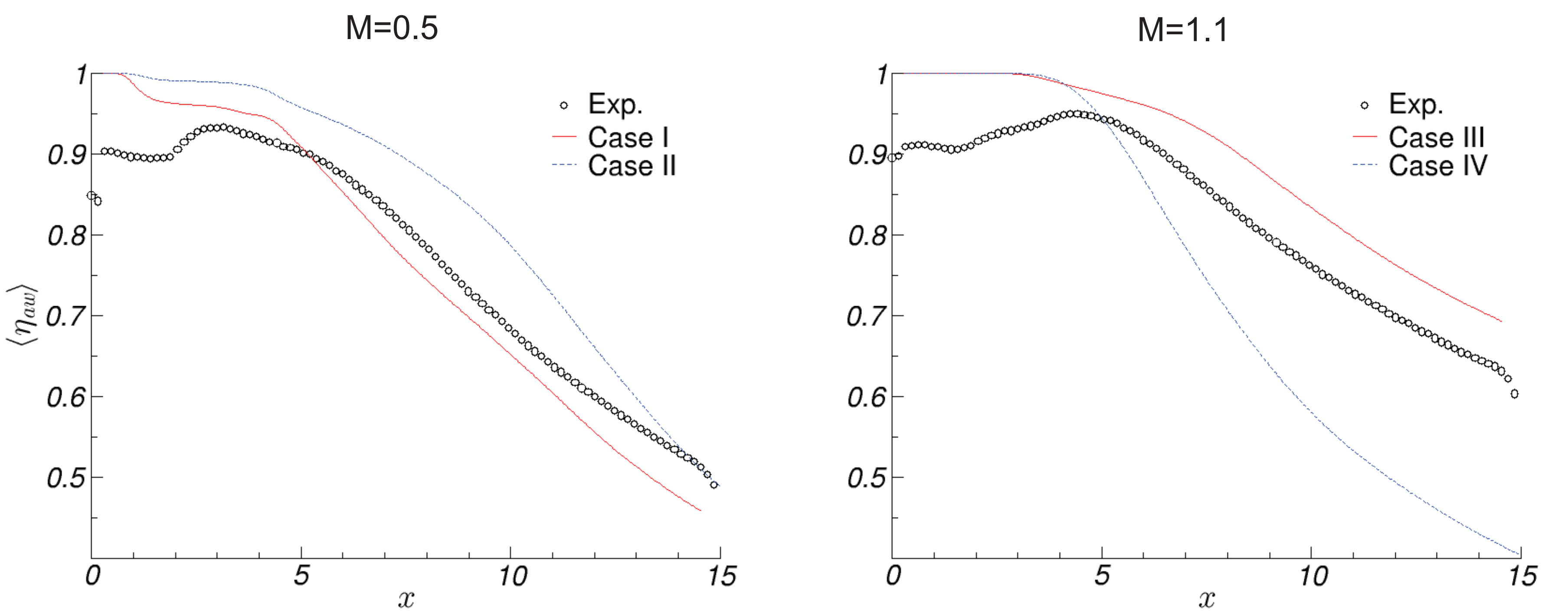
color contours of temperature and contour lines of spanwise vorticity (dashed for negative values)

Project: Trailing-edge cutback film-cooling

with Schneider & Bauer

Effect on mean wall temperature:

Adiabatic film cooling effectiveness at different blowing ratios for laminar and fully-developed turbulent coolant channel flow



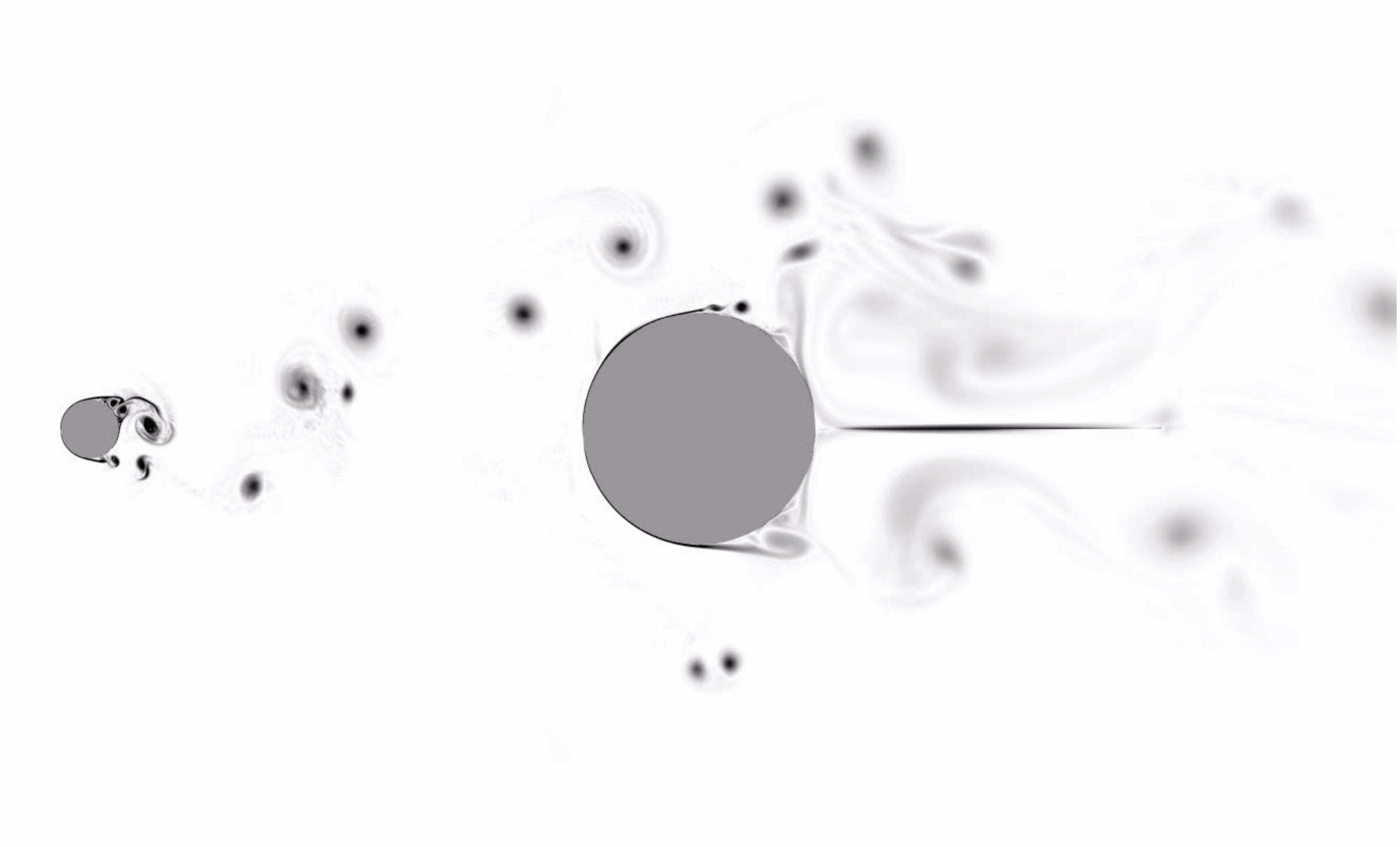
Experimental data from Martini *et al.* (2006)

Conclusions

- **DNS** is a powerful tool with **high potential** for investigating unsteady heat transfer and fluid flow phenomena, in particular for cases involving transition to turbulence and/or large coherent structures
- DNS of idealized configurations related to turbomachinery components is already **possible**
- For more realistic configurations and the inclusion of more effects, reduction of computational cost is key issue (e.g., **hybrid methods**)
- Approach pursued here: **Embedded DNS**
  (segregated coupling of DNS with LES and / or RANS)
- Embedded DNS is an **enabling technology** for many studies
- Pre-transitional heat transfer and trailing-edge cutback film-cooling are **good candidates for (embedded) DNS studies**

**THANKS TO ROLLS-ROYCE DEUTSCHLAND
AND DFG FOR SHARING THE VISION**

Thanks – Questions?



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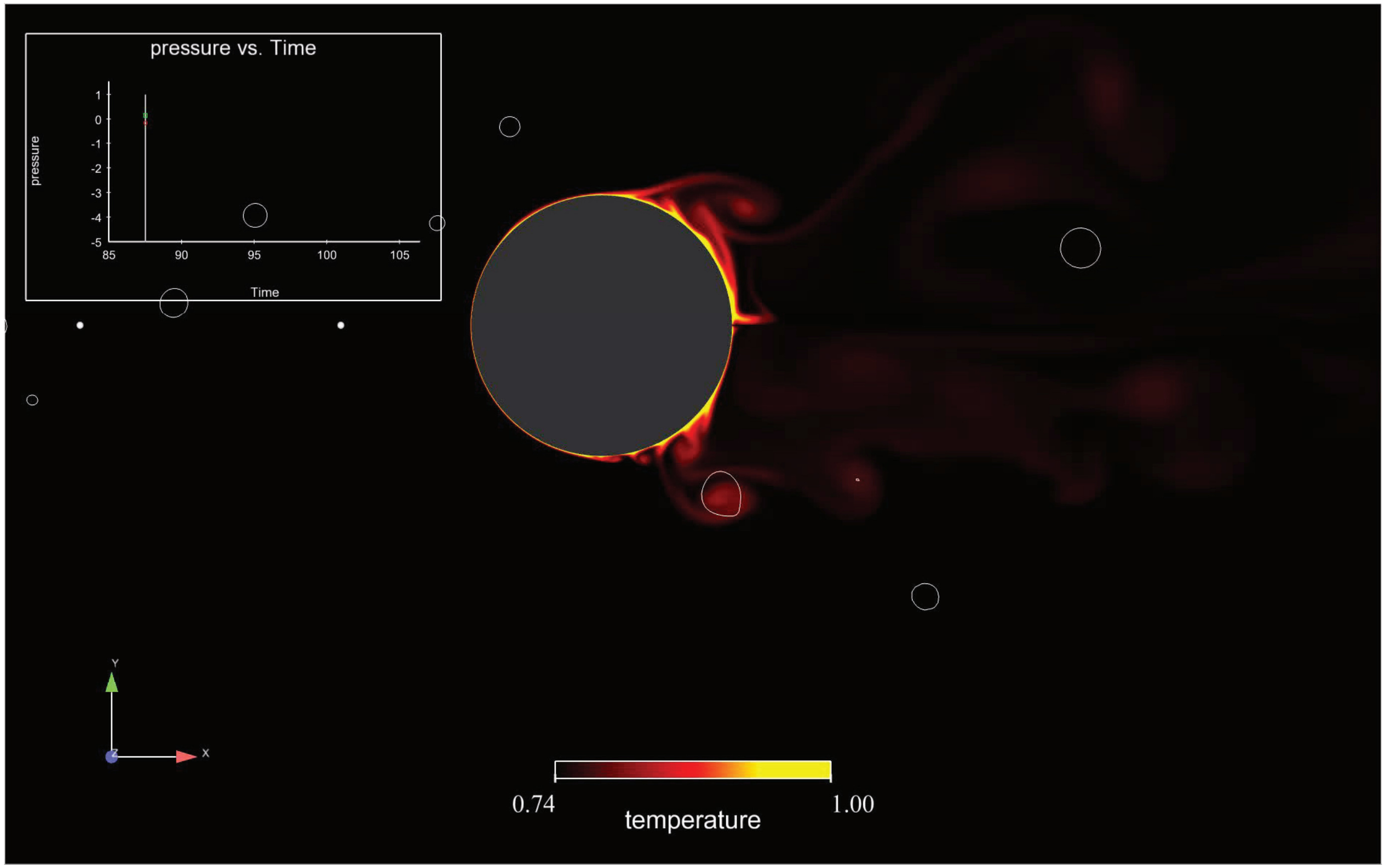
Project: Pre-transitional heat transfer

with Venema & Rodi

Instantaneous temperature and spanwise vorticity contours



Coarse simulation (two-dimensional)

Click to play animation

filename: 03t_p_isocont_dc_re48000.avi

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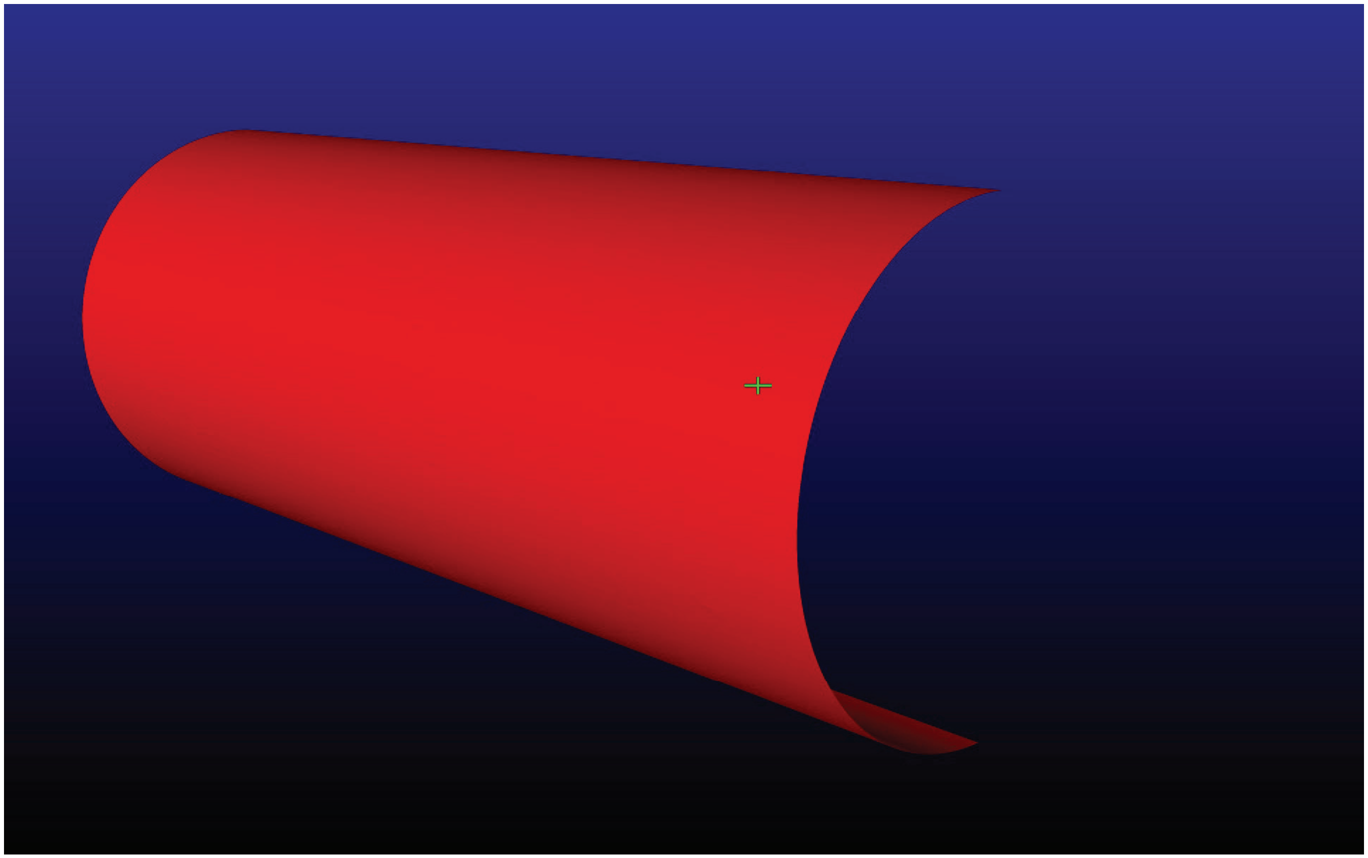
Project: Pre-transitional heat transfer

with Venema & Rodi

Instantaneous temperature contours (wall-adjacent cell at large heated cylinder)



Coarse simulation (full domain)

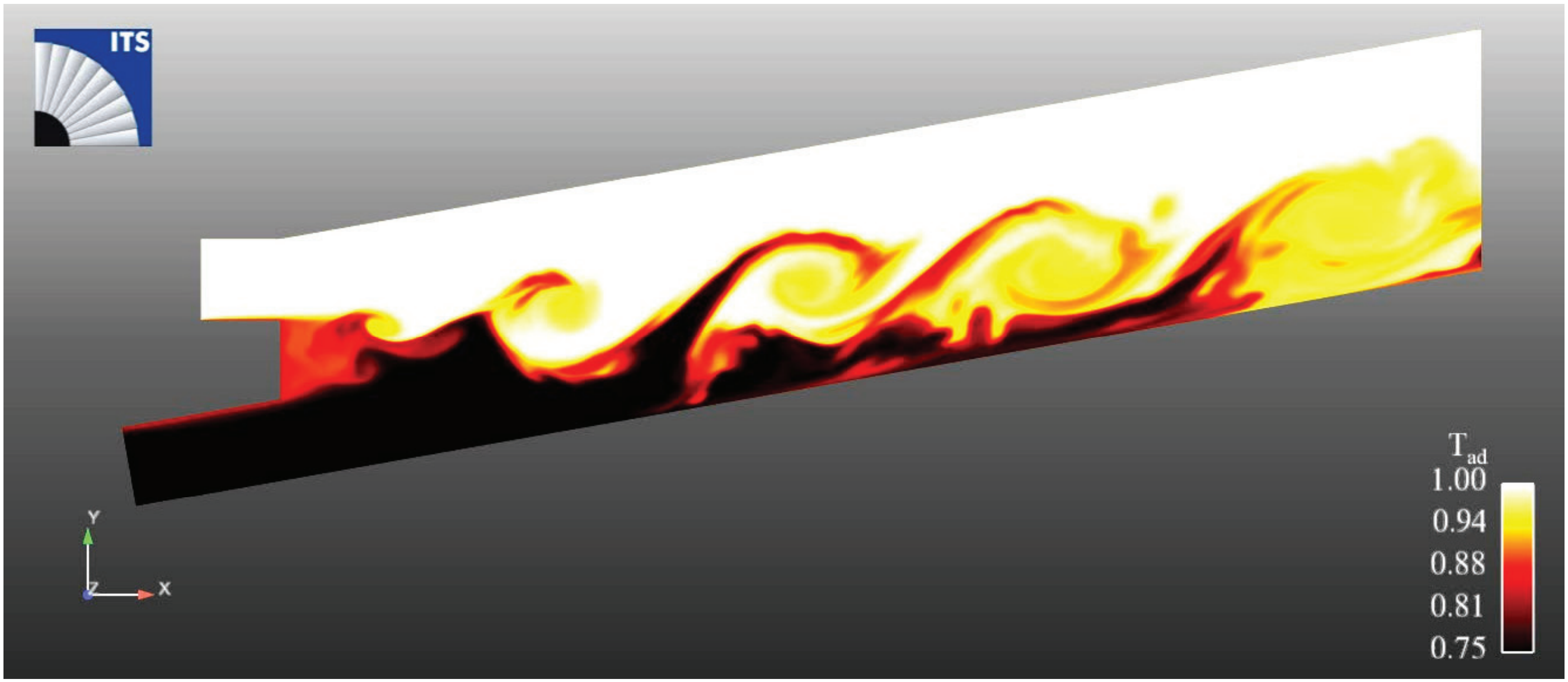
Click to play animation

filename: 03iso_temp.avi

Project: Trailing-edge cutback film-cooling

with Schneider & Bauer

Impact of coherent structures on the instantaneous flow and temperature field at the cutback for **low** **blowing ratio with turbulent coolant ejection**



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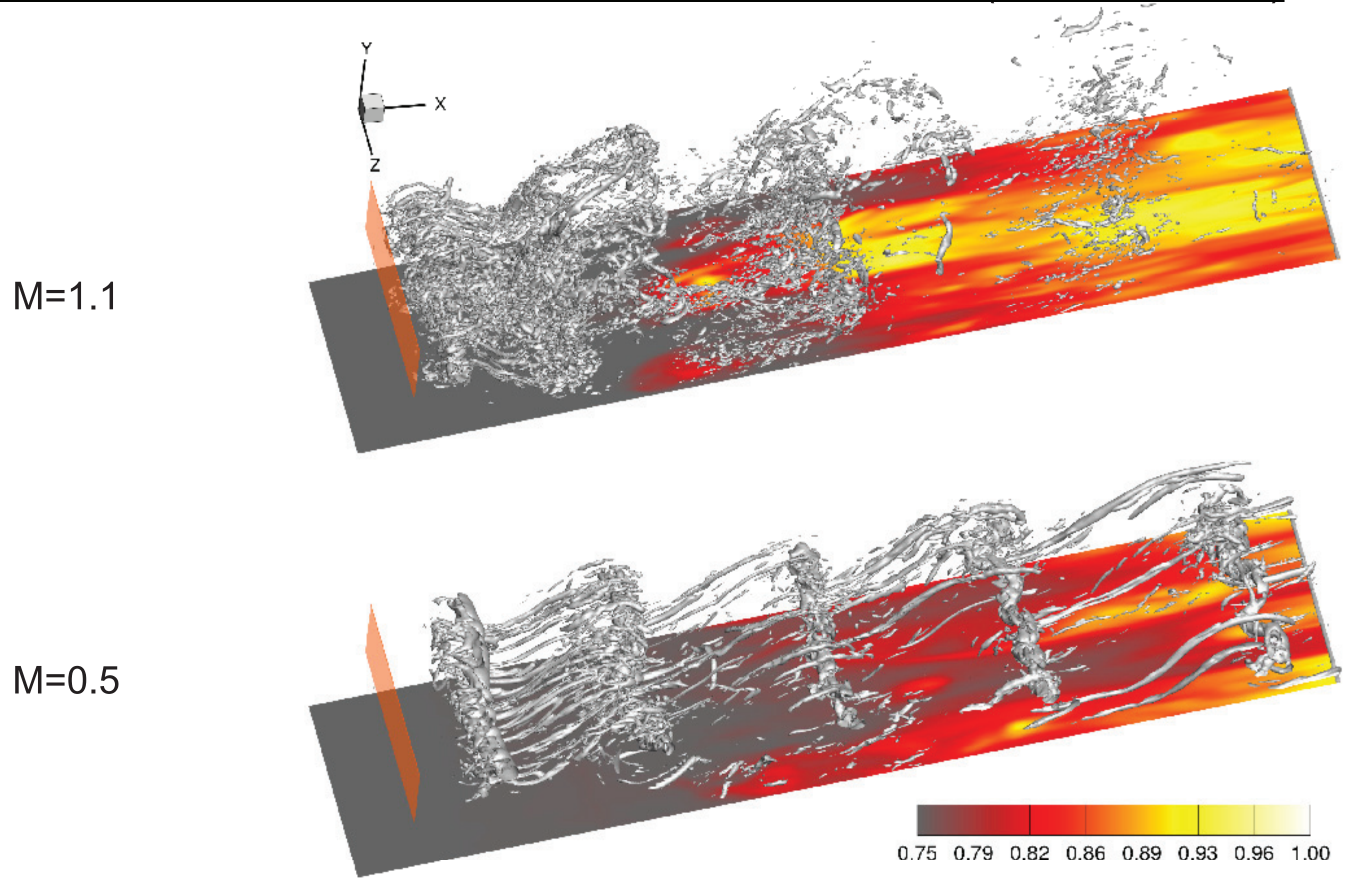
Click to play animation

filename: 03hk_movie_aiteb.avi

Project: Trailing-edge cutback film-cooling

with Schneider & Bauer

Difference in coherent structures for turbulent coolant cases (smaller scales)



color contours of temperature in wall-adjacent cells and iso-contour of vortex identification criterion Q

What is DNS – vis à vis LES and RANS ?

Direct Numerical Simulation (DNS)

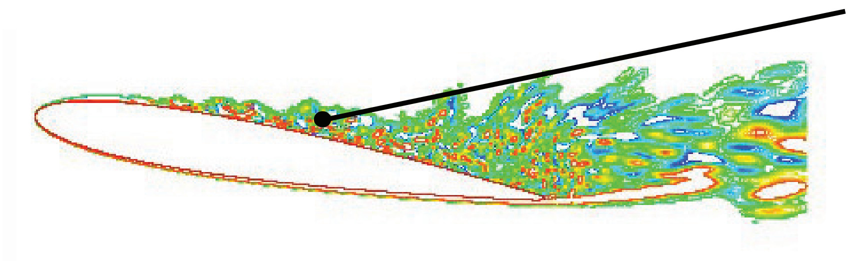
- solves numerically without turbulence modeling assumptions the governing (Navier-Stokes) equations
- all scales of motion must be resolved ⇒ extreme resolution requirements

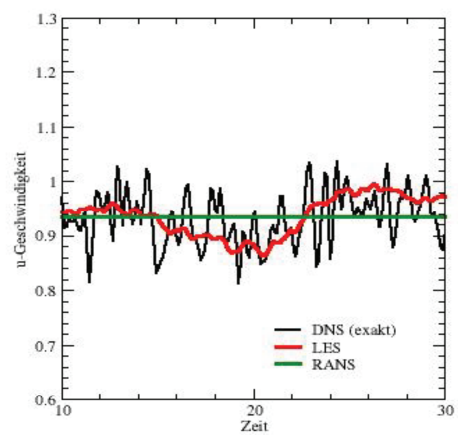
Large Eddy Simulation (LES)

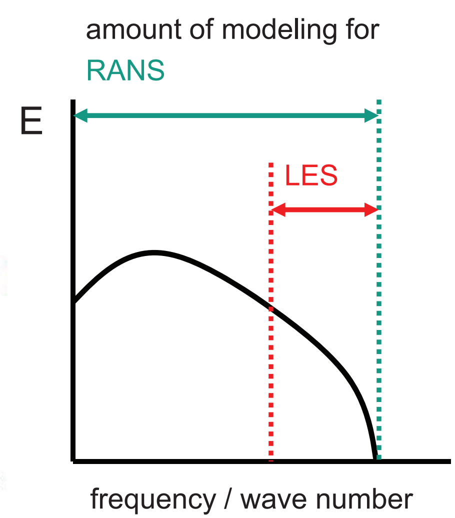
- computes large-scale motion directly
- model required to account for small-scale motion

Reynolds-Averaged Navier-Stokes (RANS) Simulation

- provides only statistical information of the flow
- model required to account for <u>all</u> fluctuations







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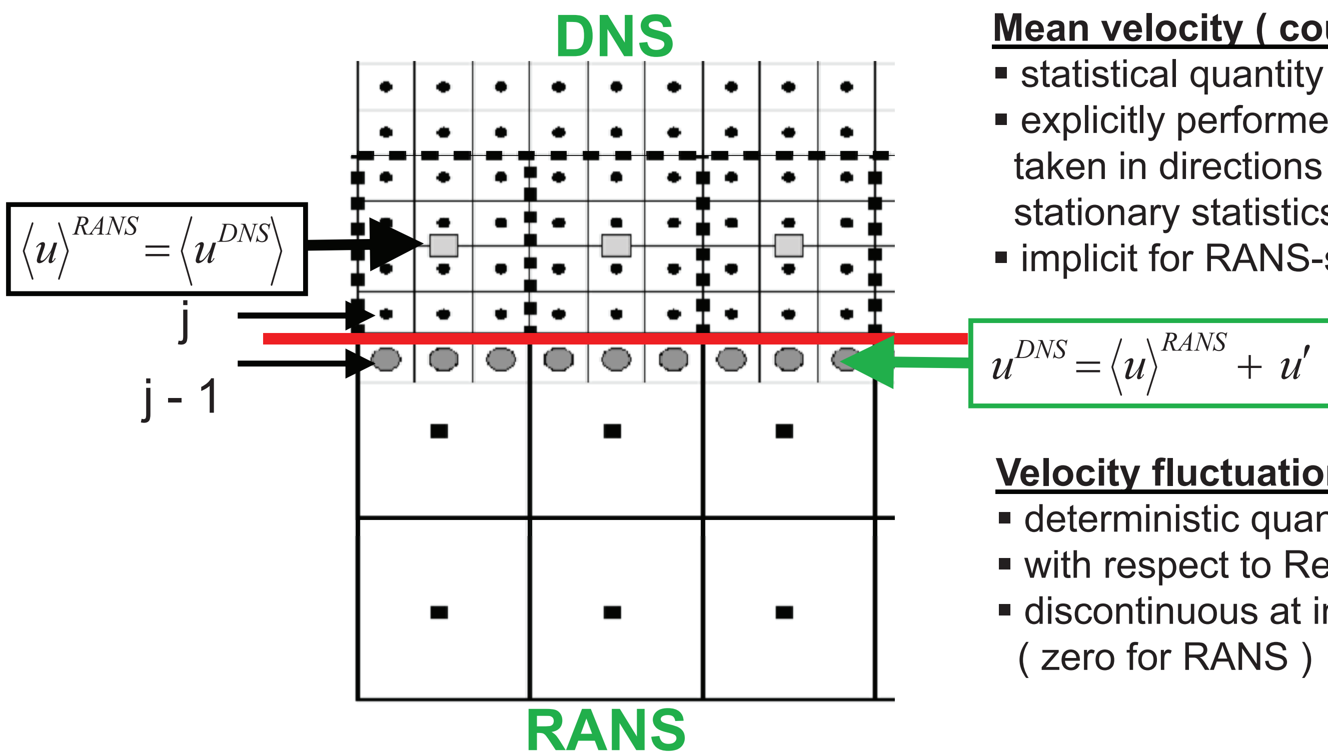
Key issue: Generation of fluctuations



Mean velocity (coupled):

- statistical quantity (Reynolds average)
- explicitly performed on DNS-side and taken in directions with homogeneous / stationary statistics
- implicit for RANS-side

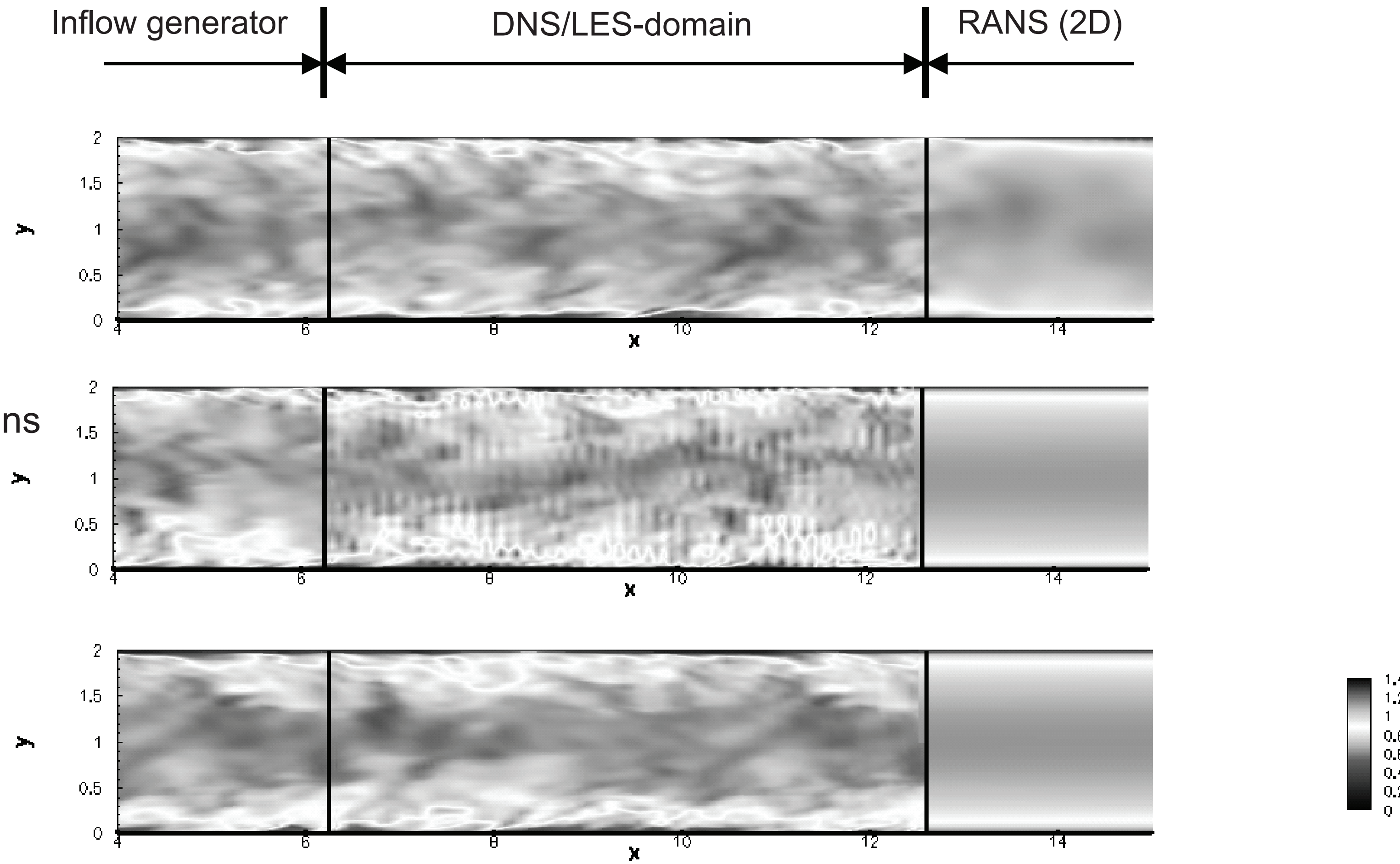
Velocity fluctuation (for DNS only):

- deterministic quantity
- with respect to Reynolds-average
- discontinuous at interface (zero for RANS)

Inflow: variations of standard turbulent inflow data generators, e.g. digital filtering, rescaling, etc.
Outflow: enrichment [Quéméré & Sagaut, 2002] or convective coupling [von Terzi & Fröhlich, 2007]

Effect of the interface

Instantaneous u-velocity contours of a turbulent channel flow (Re_τ=395):



No interface treatment

No fluctuations added

Fluctuations added (convective condition)