

DNS of Accelerating and Decelerating Turbulent Flow

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Introduction



- **Motivation**
- **Numerical Simulation Setup**
- **Results**
 - Turbulent flow
 - Relaminarization
 - Flow separation
- **Summary**



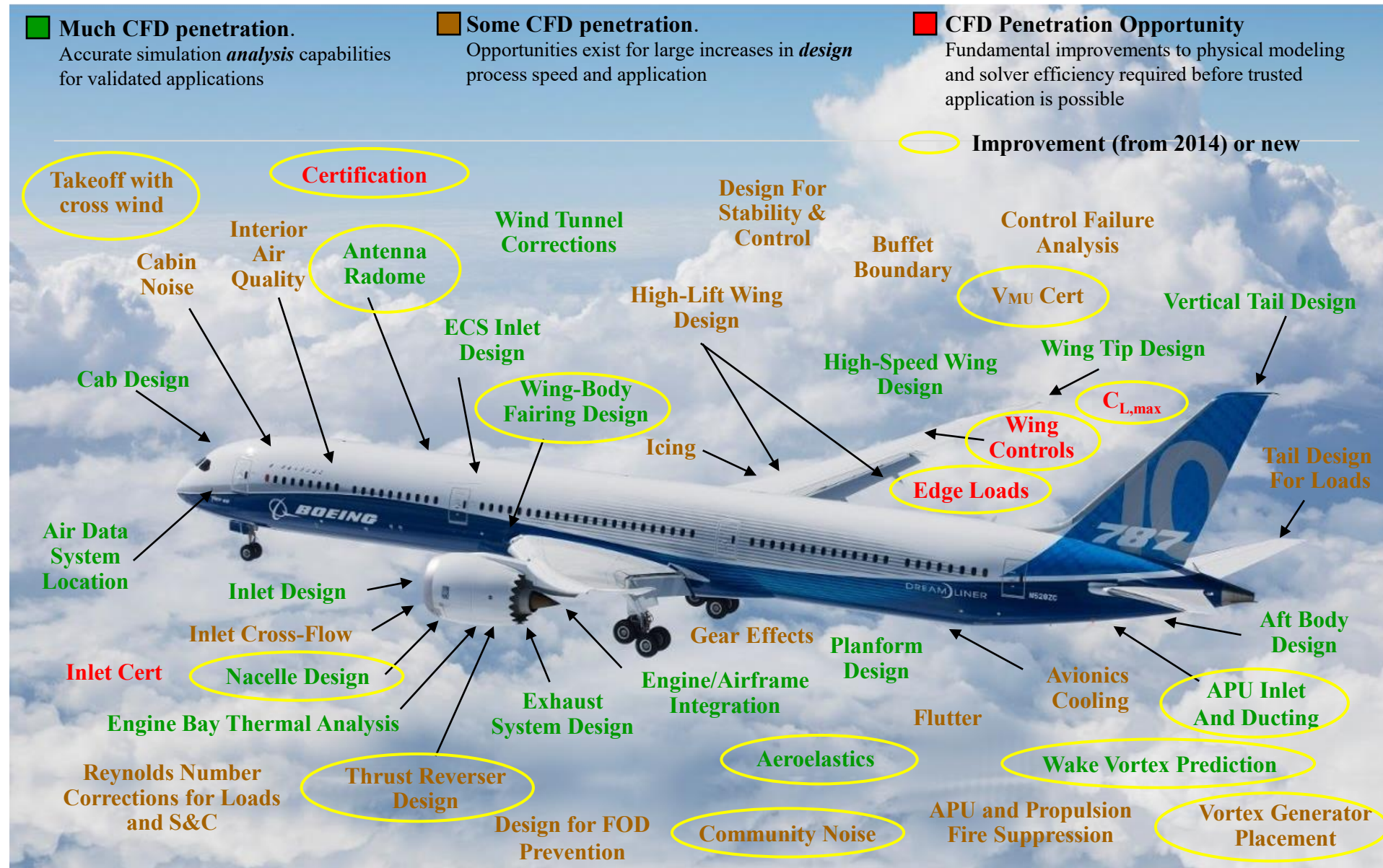
Impact of CFD on Aircraft Efficiency



“Since the first generation of jet airliners, there has been about a 40% improvement in aerodynamic efficiency and a 40% improvement in engine efficiency ... about half of that has come from CFD.”

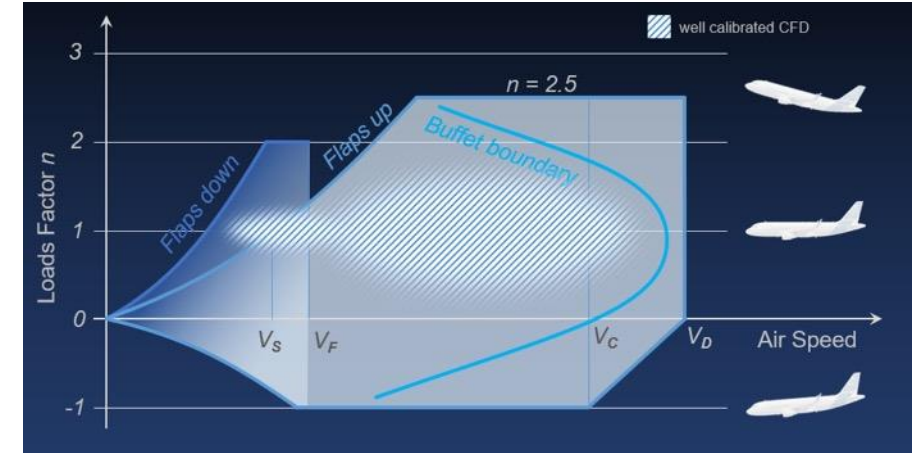
Robb Gregg, BCA Chief Aerodynamicist

During Panel Discussion Session “Transformative Aerospace System Analysis, Design and Certification: A Vision for CFD in 2030” at AIAA Aviation 2014



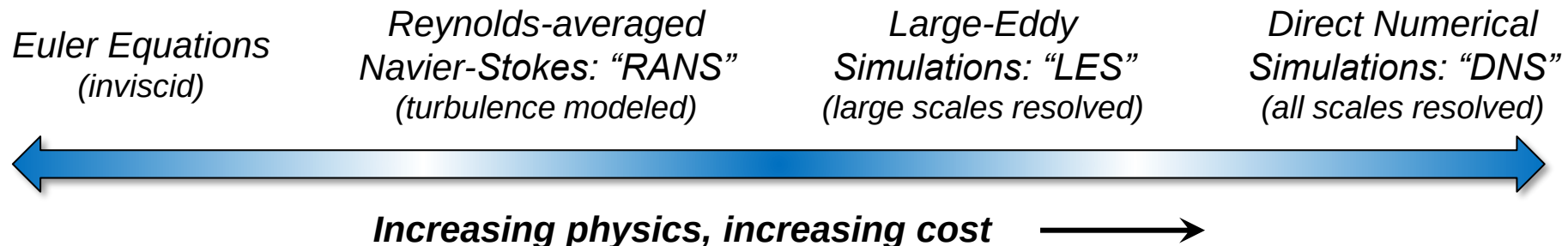
The CFD Challenge

- Current CFD technology unable to predict unsteady phenomena such as stall, buffet and flutter
 - High-lift certification flight tests account for roughly 2/3 of flight certification test points
 - 50% of flight test points replaced by computations would save about \$300 million for each aircraft development program
- The fundamental challenge is prediction of smooth body flow separation
 - This prediction capability impacts a wide range of aerospace applications
 - Eddy-resolving methods offer potential solutions, but require orders of magnitude more compute time



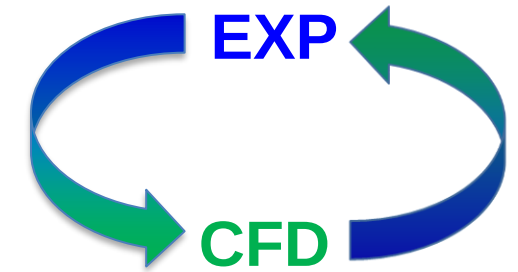
Courtesy, Boeing

- CFD has been calibrated only in **relatively small regions of the operating envelope** where the external flow is well modeled by current RANS methods
 - High-speed cruise (aero design)
 - Low-speed at nominal attitude with moderate flap settings



- **Physical Modeling and Simulations**
 - DNS/LES/WMLES, hybrid RANS/LES and Lattice-Boltzmann Method
 - Laminar-turbulent transition modeling
 - Data driven (ML-assisted) transition/turbulence modeling
- **HPC Tools and Methods**
 - Effective utilization of emerging HPC hardware
 - Accurate, efficient, and robust computational methods
 - Grid adaptation
 - Uncertainty quantification
- **CFD Validation Experiments**

Foundational research aimed at solving technical challenges



Outcome: Accurate, fully validated CFD capability

R: Robustness
C: Cost/efficiency
A: Accuracy

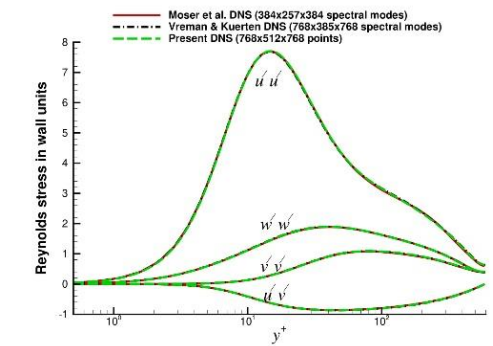
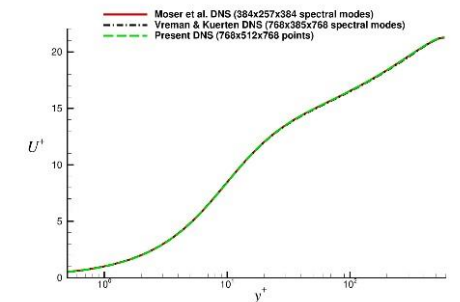
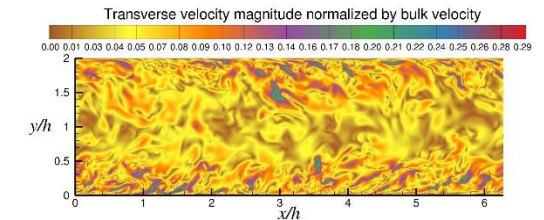


Flows Subjected to Pressure Gradients



- Flows subjected to pressure gradients are hard to predict using lower-fidelity simulation tools
 - Reynolds-averaged Navier-Stokes (RANS) do not do well, particularly smooth body flow separation due to adverse pressure gradients
- A research program underway to improve the prediction tools:
- Gaussian profile that generates favorable and adverse pressure gradients
 - Benchmark experiments
 - Large eddy simulation (LES)
 - Direct numerical simulation (DNS)
- The goal is to help develop/assess more efficient computational tools (e.g., WMLES)
 - Or, even new RANS models enabled by machine learning techniques
- This talk reports on the ongoing DNS study

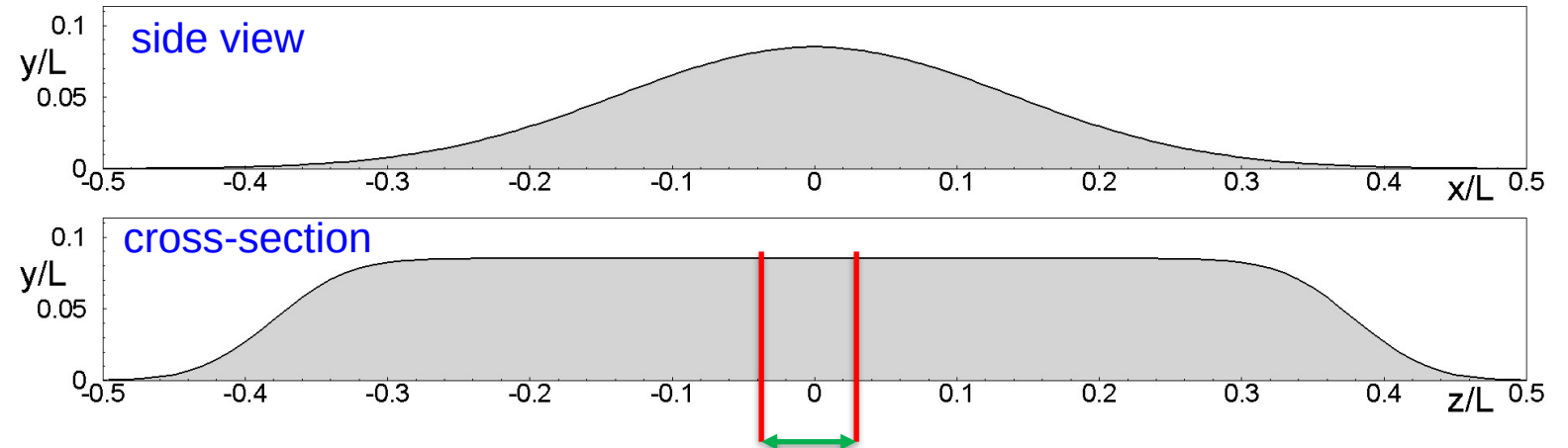
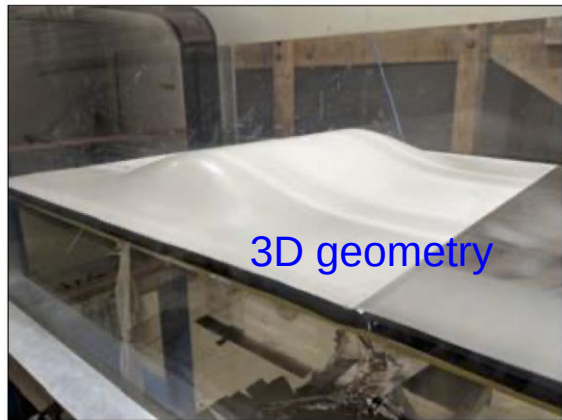
- Developed DNS flow solver based on explicit finite-difference and explicit time integration schemes to exploit GPU hardware
 - 4th-order central differencing scheme (Bogey and Baily, JCP, 2004, 194(1))
 - 6th-order optimized filter for numerical stability (Bogey and Baily, JCP, 2009, 228(1))
 - 3rd-order three-stage Runge-Kutta time integration (RK3)
 - Solver based on CUDA Fortran + MPI + Open MP
 - CUDA Fortran to launch kernels on the GPU
 - MPI for communications among GPUs
 - Host CPU mainly gets involved in MPI communications and I/O
 - OpenMP for running multiple thread on the host CPU
 - Master thread controls GPU
 - 6 helper threads handle the MPI communication
- GPU code speed up for 1 V100 GPU compared to 1 dual socket Intel Skylake is about **5X**



Excellent agreement with previous
channel flow simulations

The Gaussian Bump

- Full geometry is defined by the following equation:
 - $y(x, z) = 0.5h[1 + \text{erf}((0.5L - 2z_0 - |z|)/z_0)] \exp[-(x/x_0)^2]$
 - where $h = 0.085L$, $x_0 = 0.195L$, $z_0 = 0.06L$

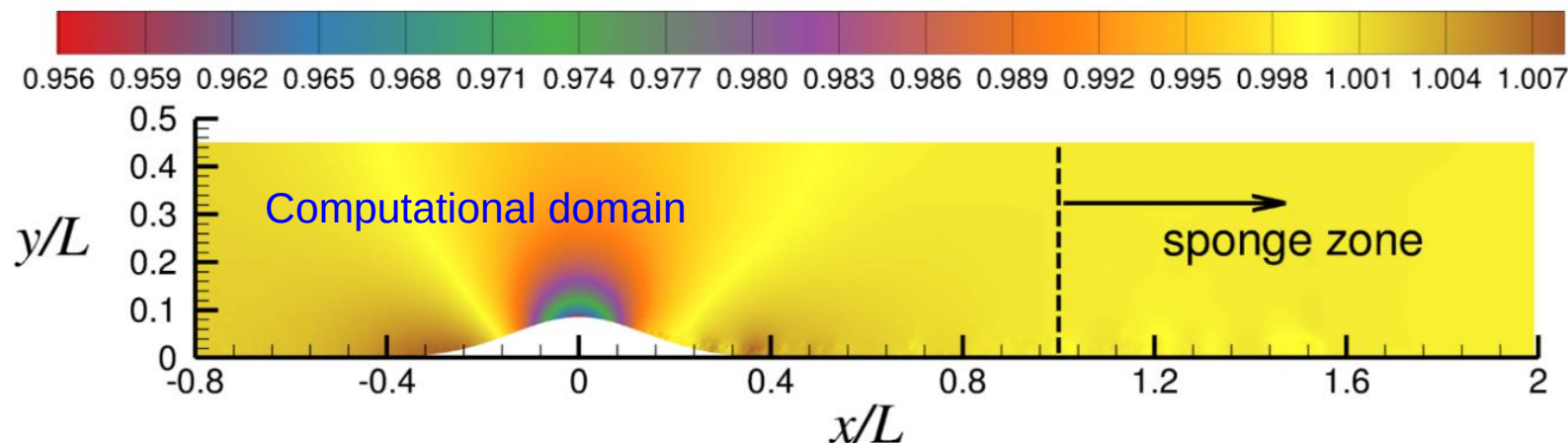


- Experiment will measure
 - Surface pressures
 - Skin-friction distribution
 - Velocity and Reynolds stress profiles
 - Using PIV and LDV

DNS for a small
spanwise extent
only

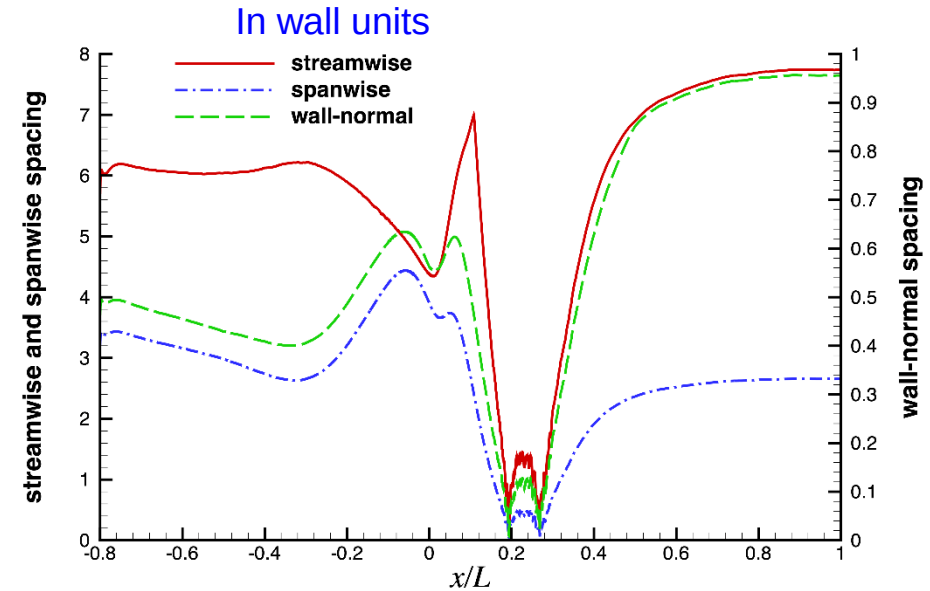
Spanwise-Periodic DNS Schematic

- Due to limited computational resources, **span set to $0.04L$**
- **Reynolds number** (based on upstream velocity and L) = **1 million**
 - Inflow momentum-thickness Reynolds number, $Re_\theta \approx 530$; at $x/L = -0.4$, $Re_\theta \approx 1600$
- Freestream **Mach number = 0.2**
- RANS data to set up mean inflow and top plane boundary conditions
- Turbulent inflow generation based on the recycling/rescaling method
- Viscous isothermal boundary condition on lower wall
- Sponge zone with characteristic boundary condition on outflow boundary

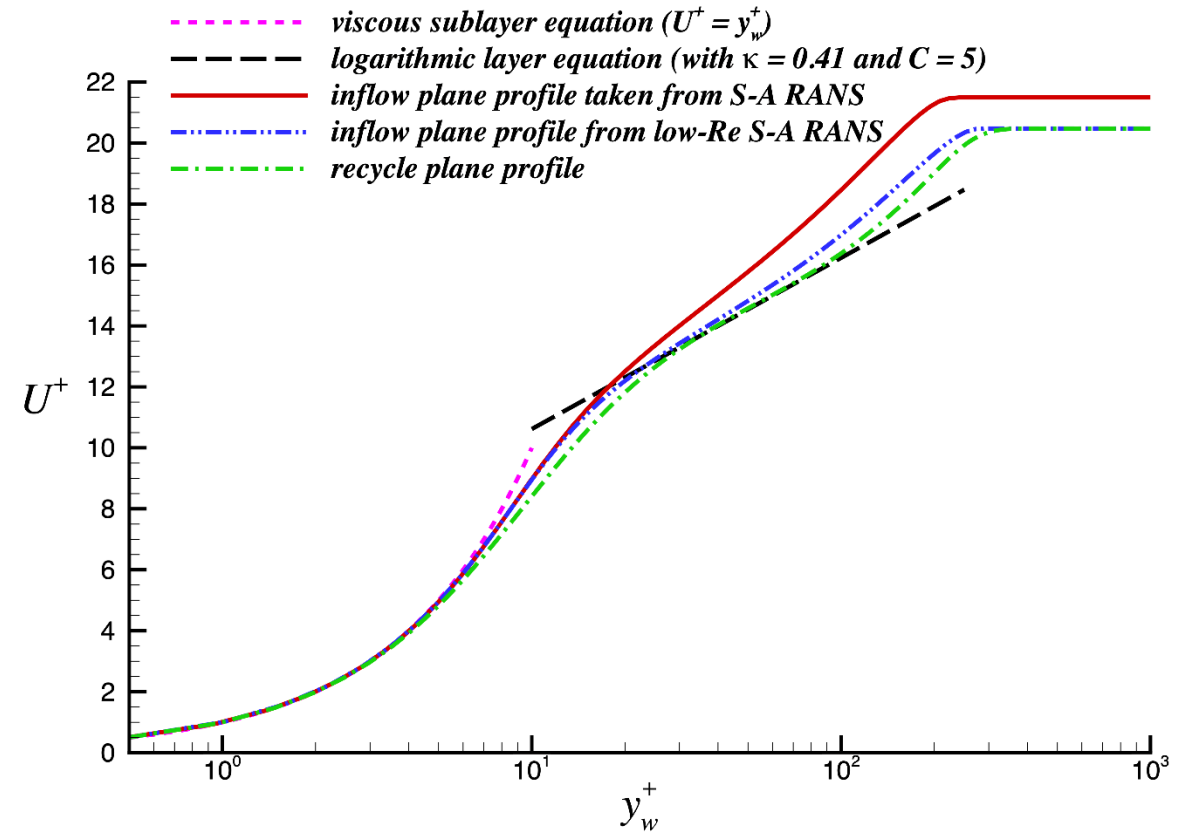


Contours denote the instantaneous pressure normalized by reference value

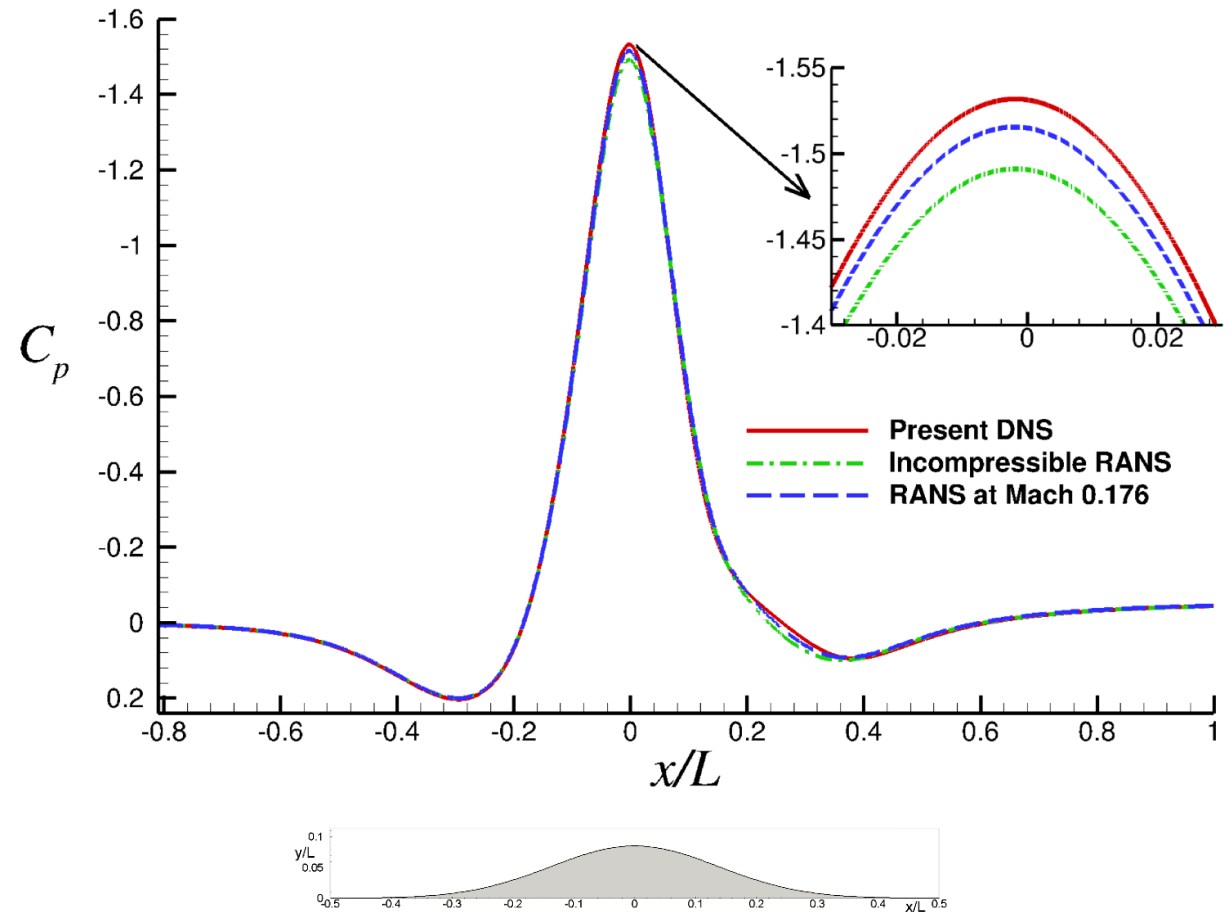
- 2.265 billion grid points (12288x320x576)
 - Largest streamwise spacing: 6 to 8 wall units
 - Largest spanwise spacing: 4.5 units
 - First wall-normal spacing: 0.4 to 0.95 units
 - Wall-normal spacing near BL edge: 10 units
- 750,000 steps to compute a time interval of L/U_∞
- 48 NVIDIA V100 GPUs, each with 32 GB memory, to perform the DNS
- Two months of run time to compute a time interval of $20 L/U_\infty$
- Flow statistics gathered over $15 L/U_\infty$



- RANS data to set up mean inflow
 - Standard Spalart-Allmaras (SA) model
- Turbulent inflow generation based on the recycling/rescaling method solution (Uzun & Malik, AIAA J., Vol. 56, No. 2, 2018, pp. 715-730).
- DNS mean solution follows log-law
 - RANS profile differs due to low Reynolds number
 - Comparison improves when low Re correction to SA model is used



- Overall good agreement between DNS and RANS
- The sense of streamwise pressure gradient changes at the foot, apex and tail of the bump; this will trigger the formation of internal layers



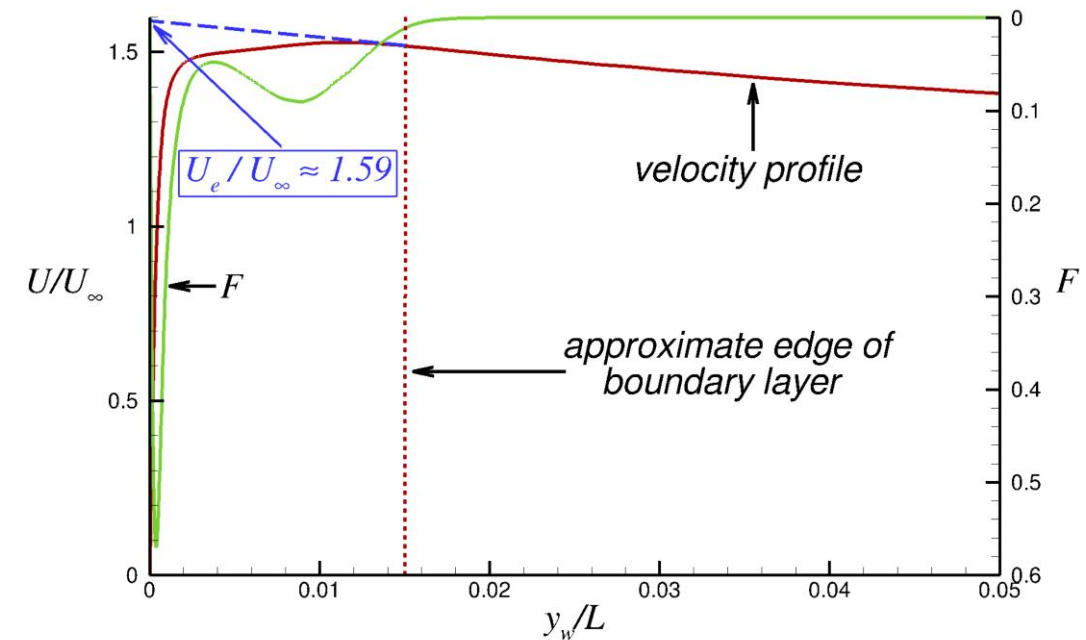
- Spalart and Watmuff (*JFM*, 1993) proposed the following integrals based on spanwise vorticity to compute boundary layer edge velocity & displacement and momentum thicknesses for incompressible flow

$$U_e = \int_0^{\infty} -\omega_z(y_w) dy_w$$

$$\delta^* = \frac{1}{U_e} \int_0^{\infty} -y_w \omega_z(y_w) dy_w$$

$$\theta = \frac{2}{U_e^2} \int_0^{\infty} y_w \left[\int_0^{y_w} \omega_z(n) dn \right] \omega_z(y_w) dy_w - \delta^*$$

y_w is the wall-normal distance, ω_z is the mean spanwise vorticity



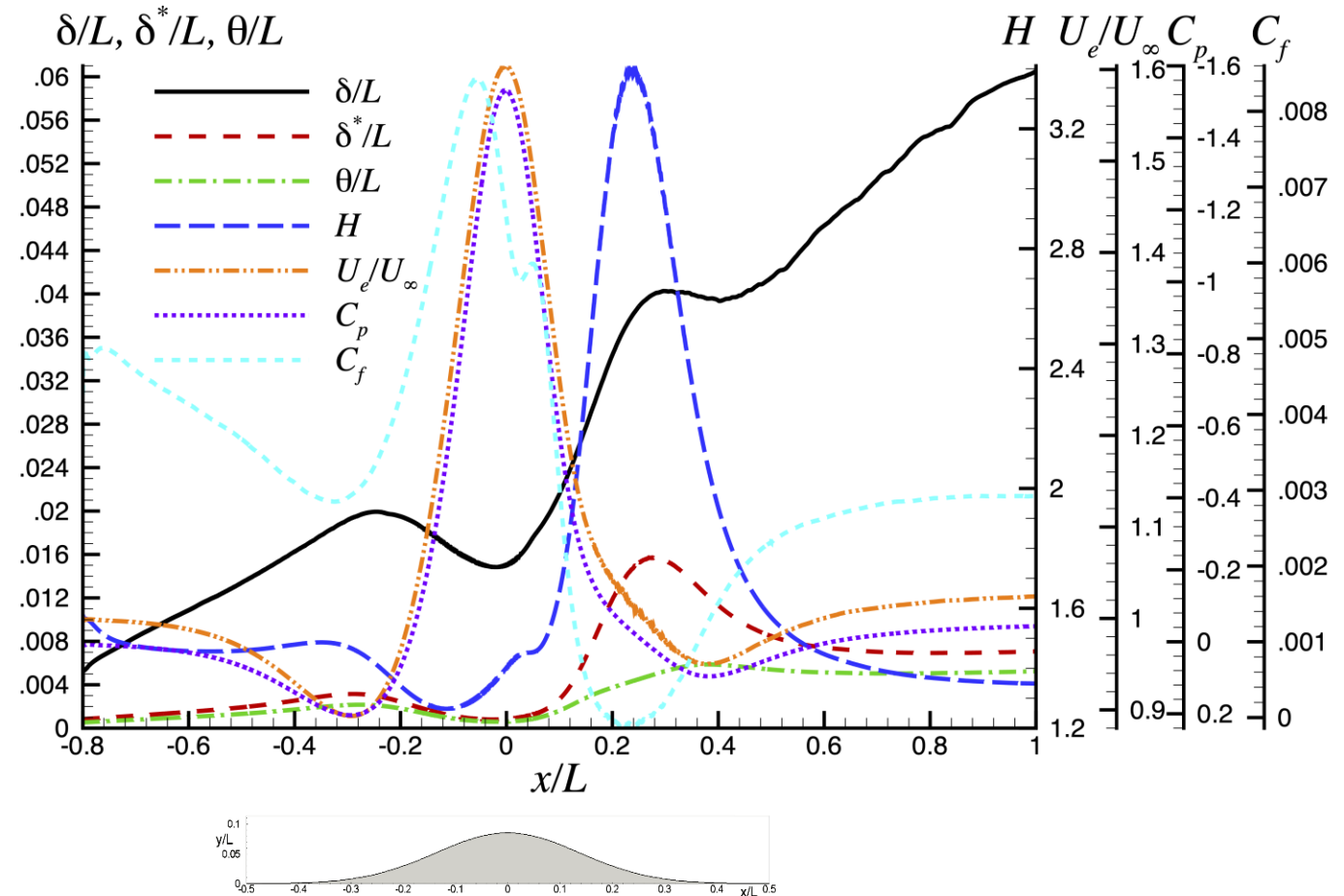
$$F = -y_w \omega_z$$

at $y_w/L \approx 0.015$

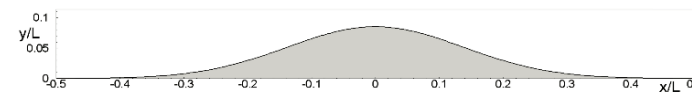
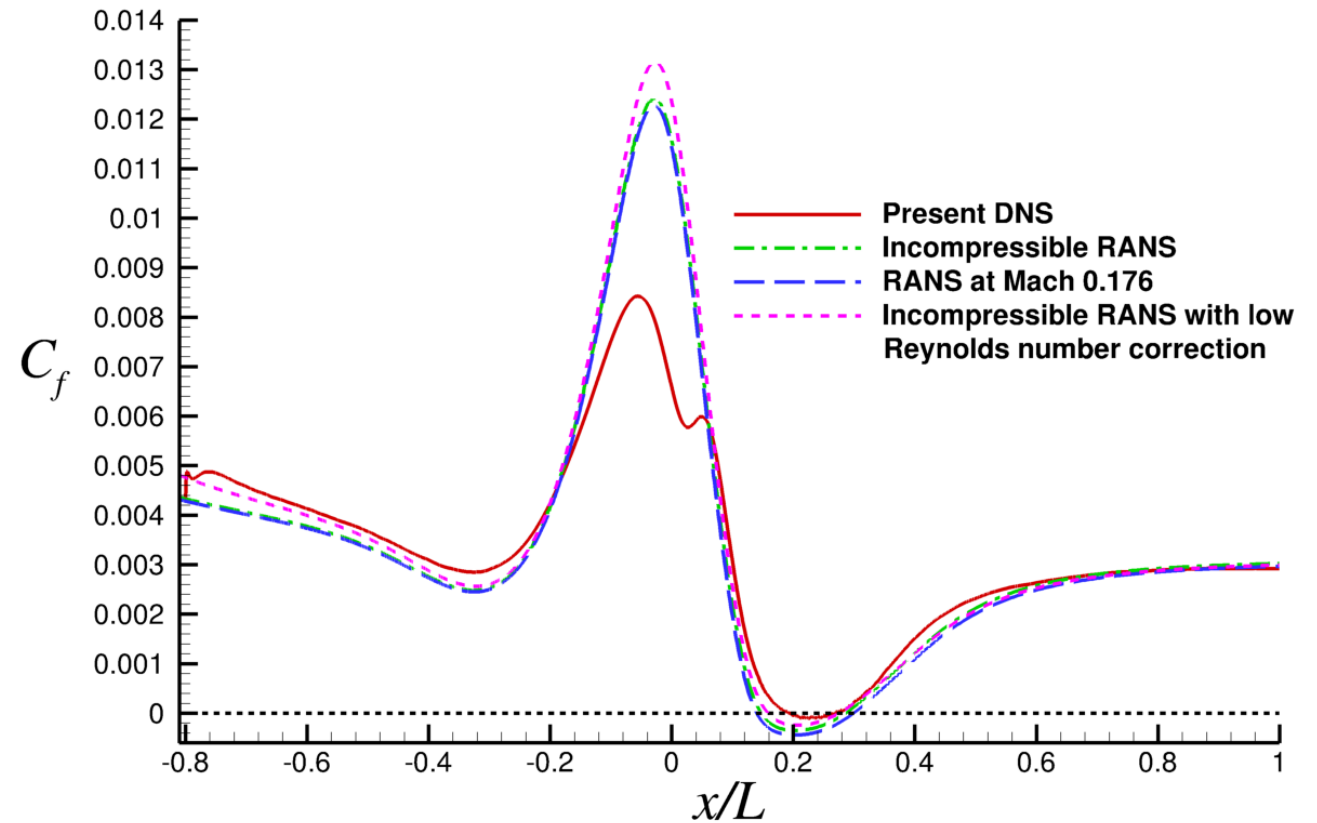
$$F \approx 0.02 F_{max}$$

Variation of Mean Boundary Layer Properties

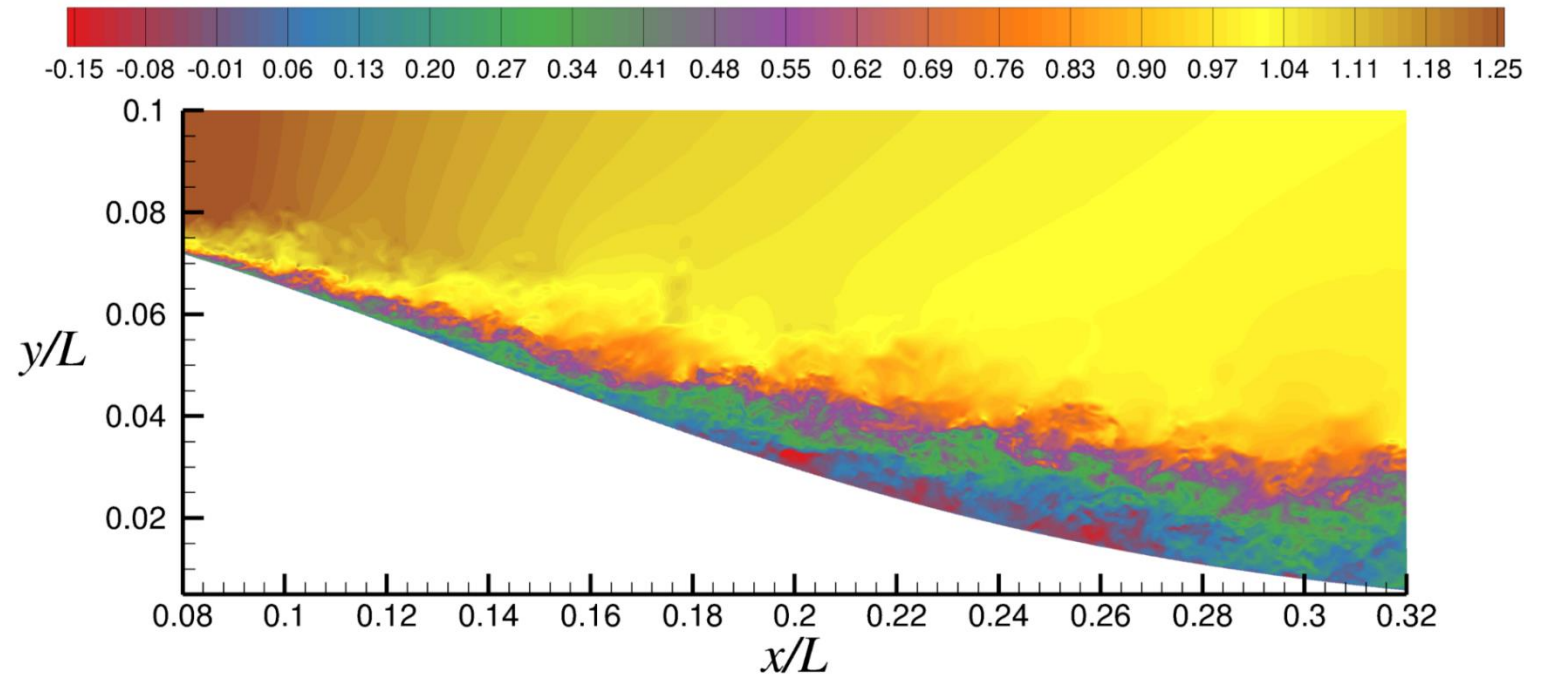
- Flow goes through significant changes due to pressure gradients
 - boundary layer thickness
 - displacement thickness
 - momentum thickness
 - shape factor
 - edge velocity
 - surface pressure coefficient
 - skin-friction coefficient



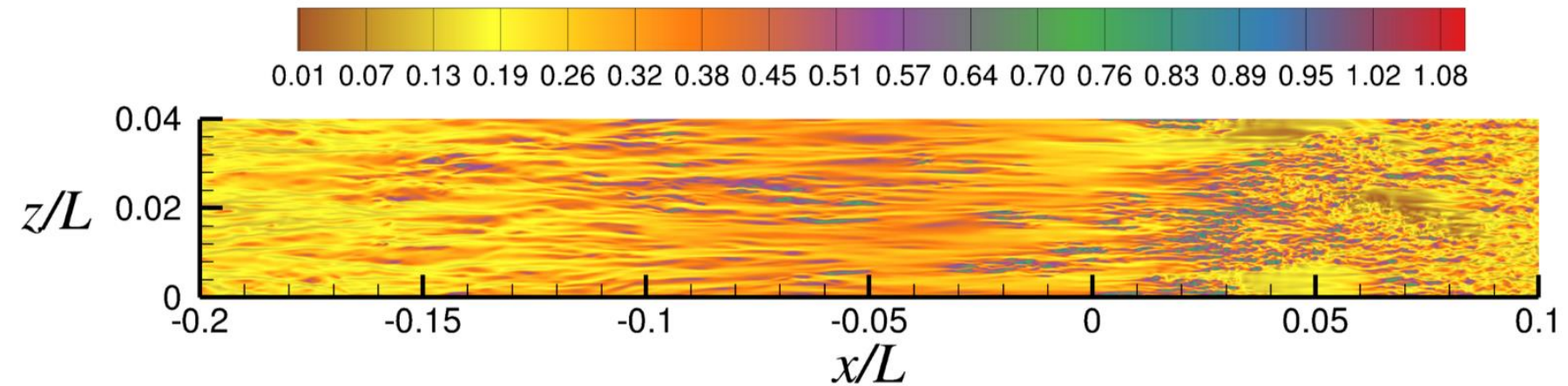
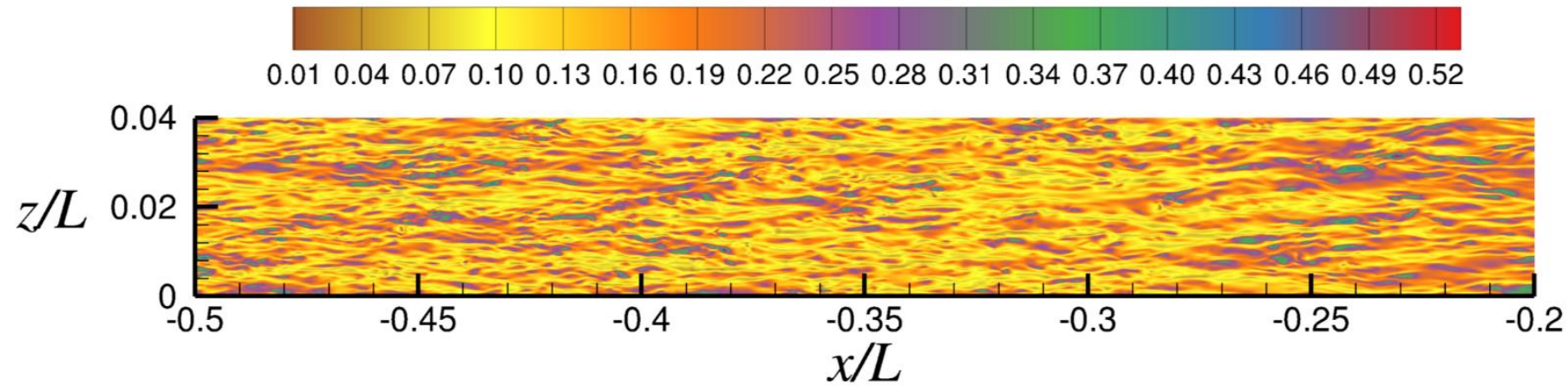
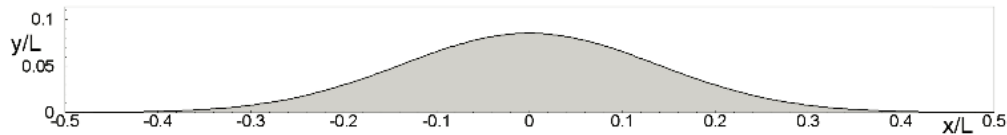
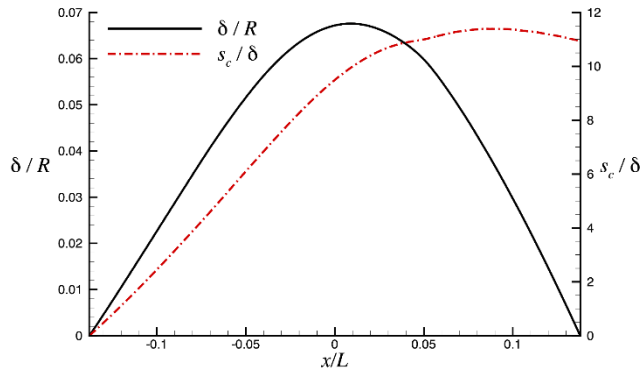
- RANS predict much higher peak skin friction levels
 - DNS skin-friction lower due to relaminarization, caused by the combination of low Re and strong favorable pressure gradient
- DNS yields very mild flow separation (incipient)
 - RANS predicts larger separation
 - RANS with curvature correction (not shown) gives even larger separation



- Flow visualization shows incipient or very weak flow separation in the aft section
 - Contours denote the instantaneous axial velocity normalized by reference velocity



- Combination of low Reynolds number, strong favorable pressure gradient and **convex curvature** leads to flow relaminarization/stabilization upstream of apex

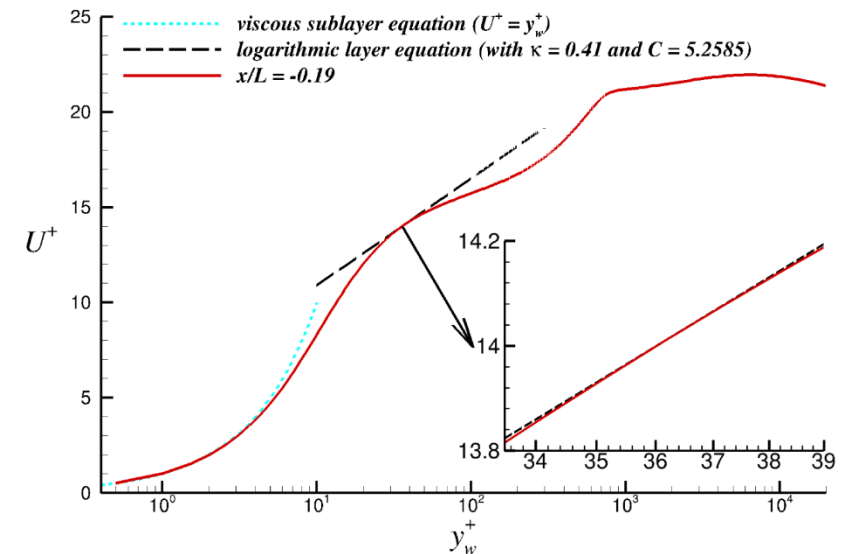
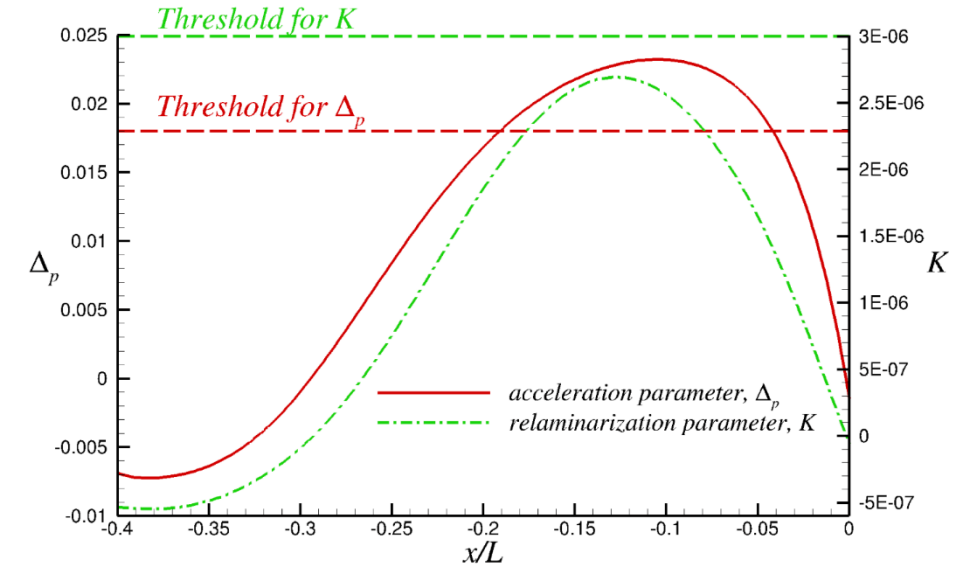


Normalized total velocity contours on a near-wall plane where $4 \lesssim y_w^+ \lesssim 6$

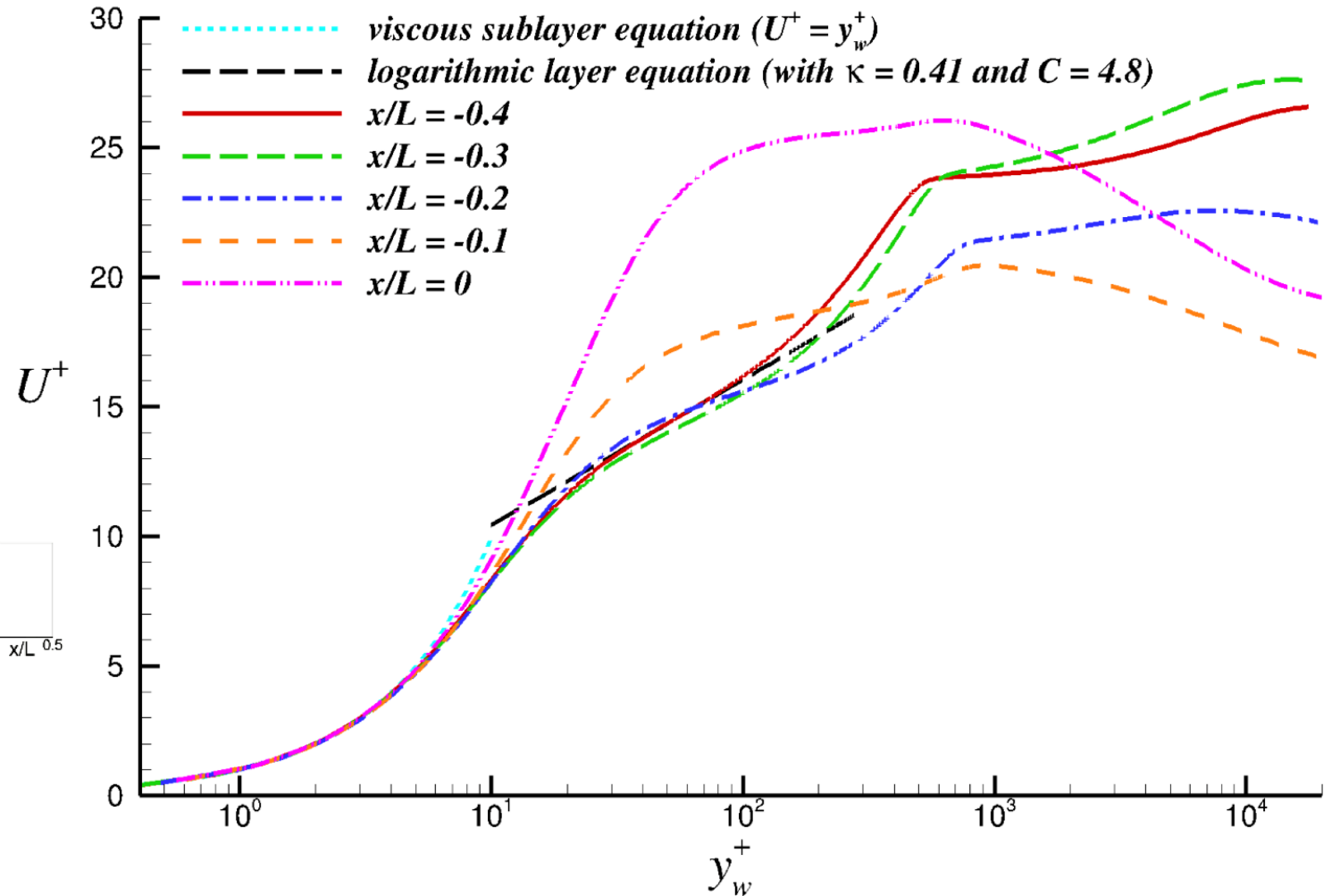
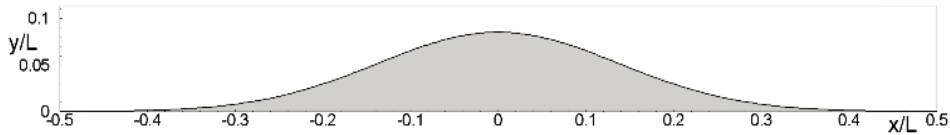
- Patel and Head (*JFM*, 1968) concluded that:
 - “Major departures” from logarithmic layer occur when Δ_p exceeds the threshold value of 0.018

$$\Delta_p = -\frac{\nu}{\rho u_\tau^3} \frac{\partial p}{\partial s}$$

$$\Delta_p = 0.018 \text{ at } \frac{x}{L} \approx -0.19$$

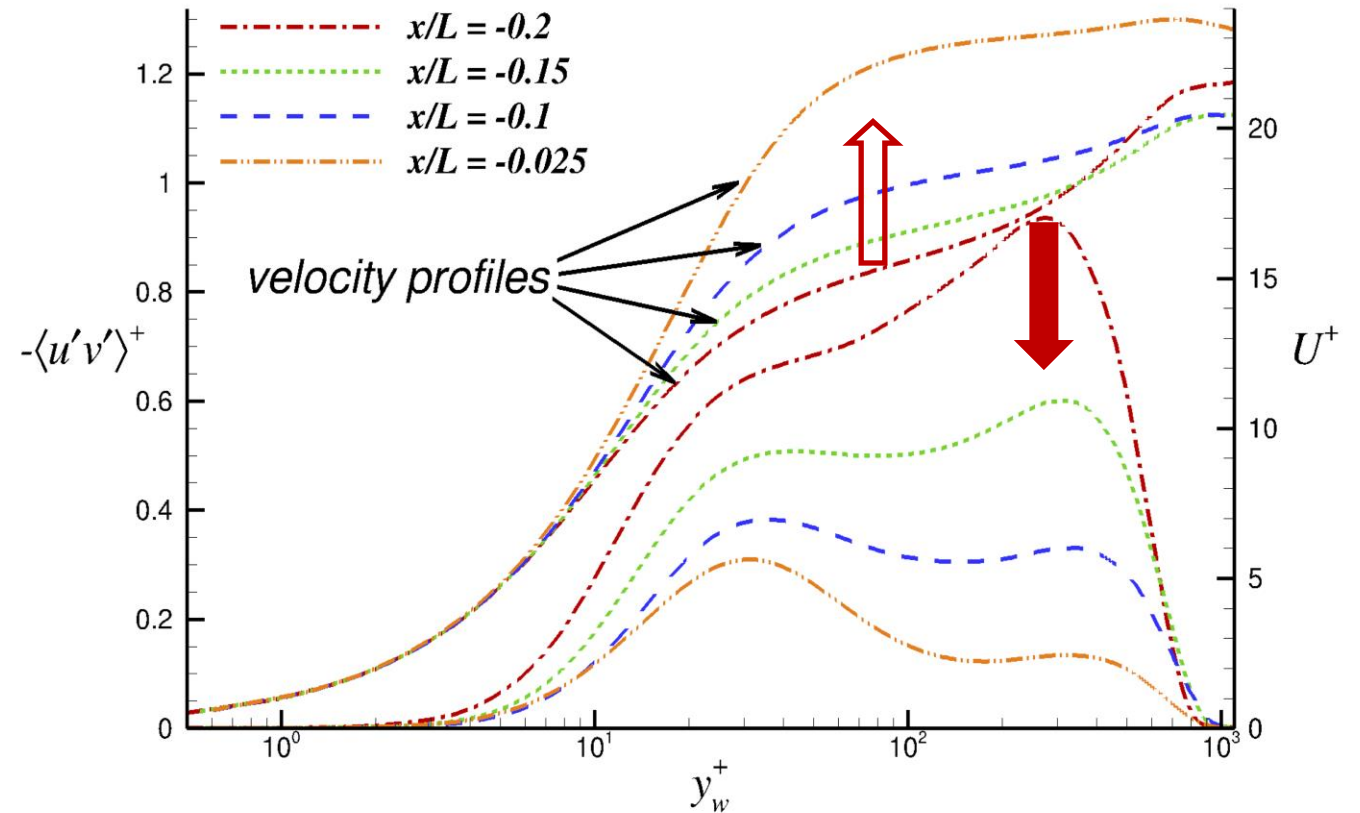
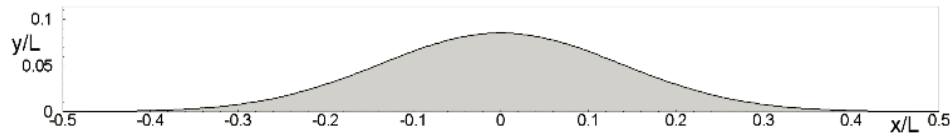


- Velocity profiles continue to depart from the log-law as the flow tends toward relaminarization in the accelerated flow region

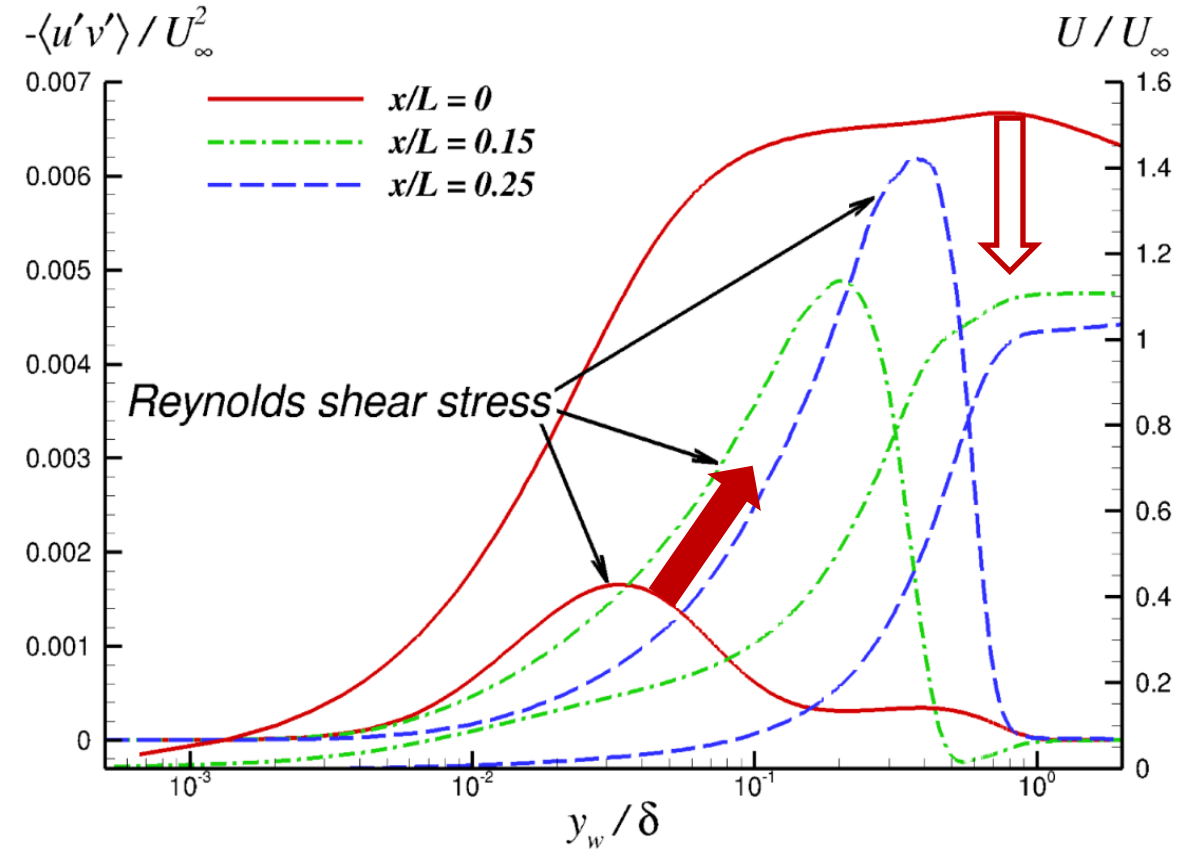
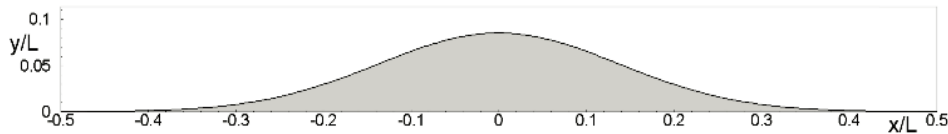


Shear Stress and Velocity Profiles in Accelerating Flow Region

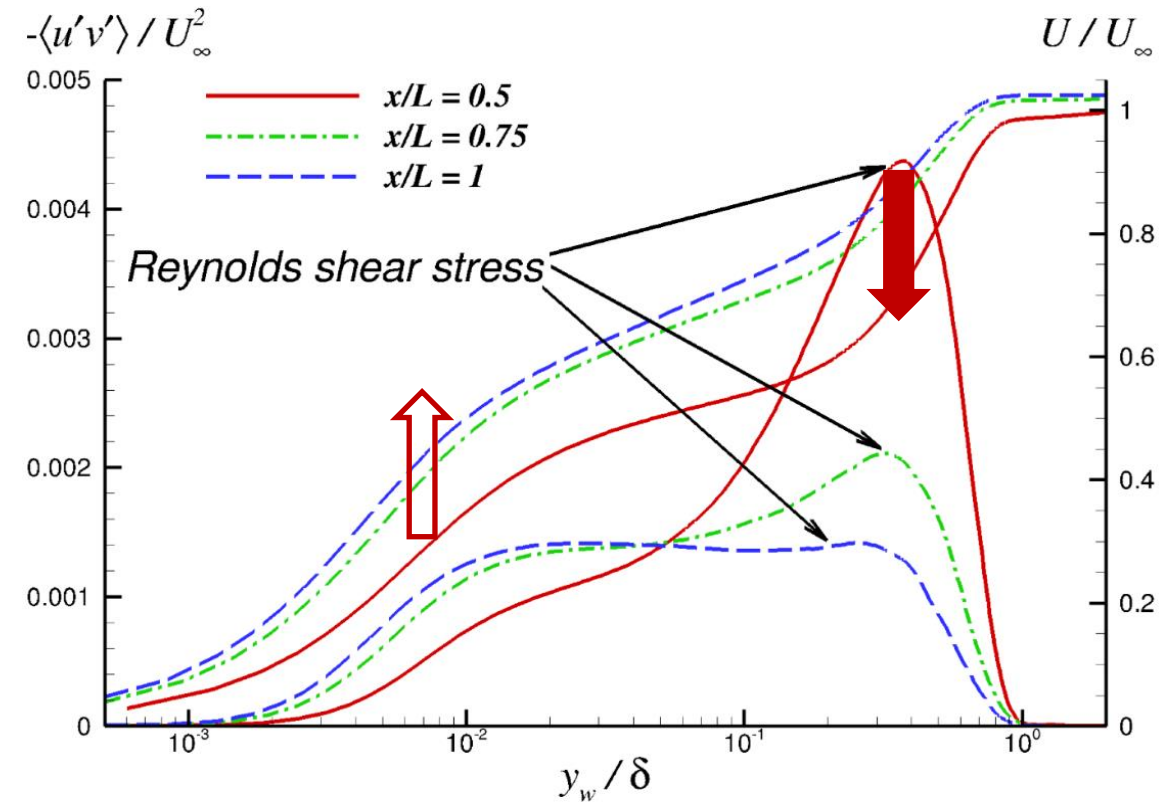
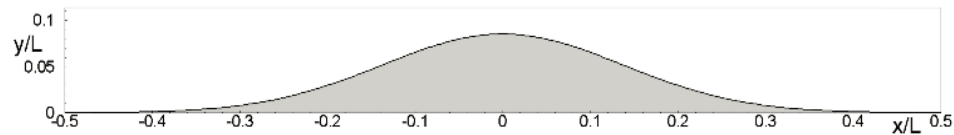
- Original outer peak decays due to reduction in velocity gradient in outer region by flow acceleration
- An **inner stress peak** develops in the internal layer, but its growth is hampered by flow stabilization



- Deceleration leads to the formation of a **buffer layer** between low- and high-speed regions; this buffer zone acts like a **free shear layer** and can be viewed as a new internal
- Shear stress peak shifts from the near-wall region to the free shear layer, which also contains the normal stress peaks



- The weakly favorable pressure gradient in recovery region reduces the velocity gradient in the free shear layer region; shear and normal stress peaks start to decay
- Another internal layer develops near the wall; but the domain is not long enough for the inner stress peak to fully form



- Combination of low Reynolds number, favorable pressure gradient and convex surface curvature leads to flow local relaminarization in the accelerating region
 - Patel and Head's threshold value of 0.018 for the acceleration parameter was found to reasonably predict the breakdown of logarithmic layer in the accelerating region
 - As expected, RANS fails to detect this phenomenon
- Present DNS predicts incipient or very weak separation in the adverse pressure gradient region
 - In comparison, RANS yields much stronger separation
- A higher Reynolds number case of the same geometry, that would preclude relaminarization, with a wider span, is currently underway
- These results will be compared with results from ongoing full 3D wall-modeled large eddy simulation (WMLES) and experimental results
 - Mean flow development
 - Skin-friction
 - Reynolds stress profiles



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