Status of Turbulence Modelling at ANSYS

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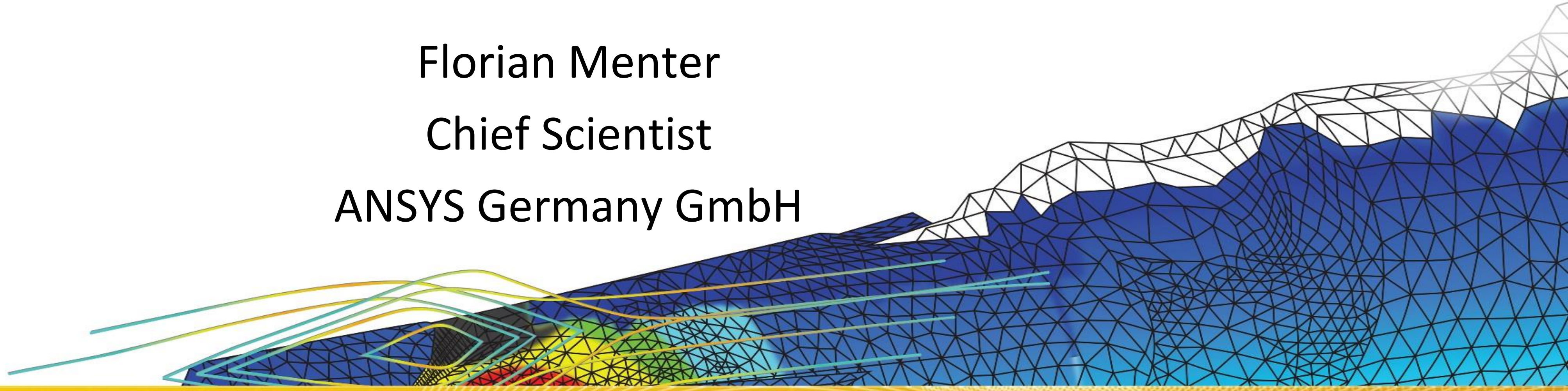
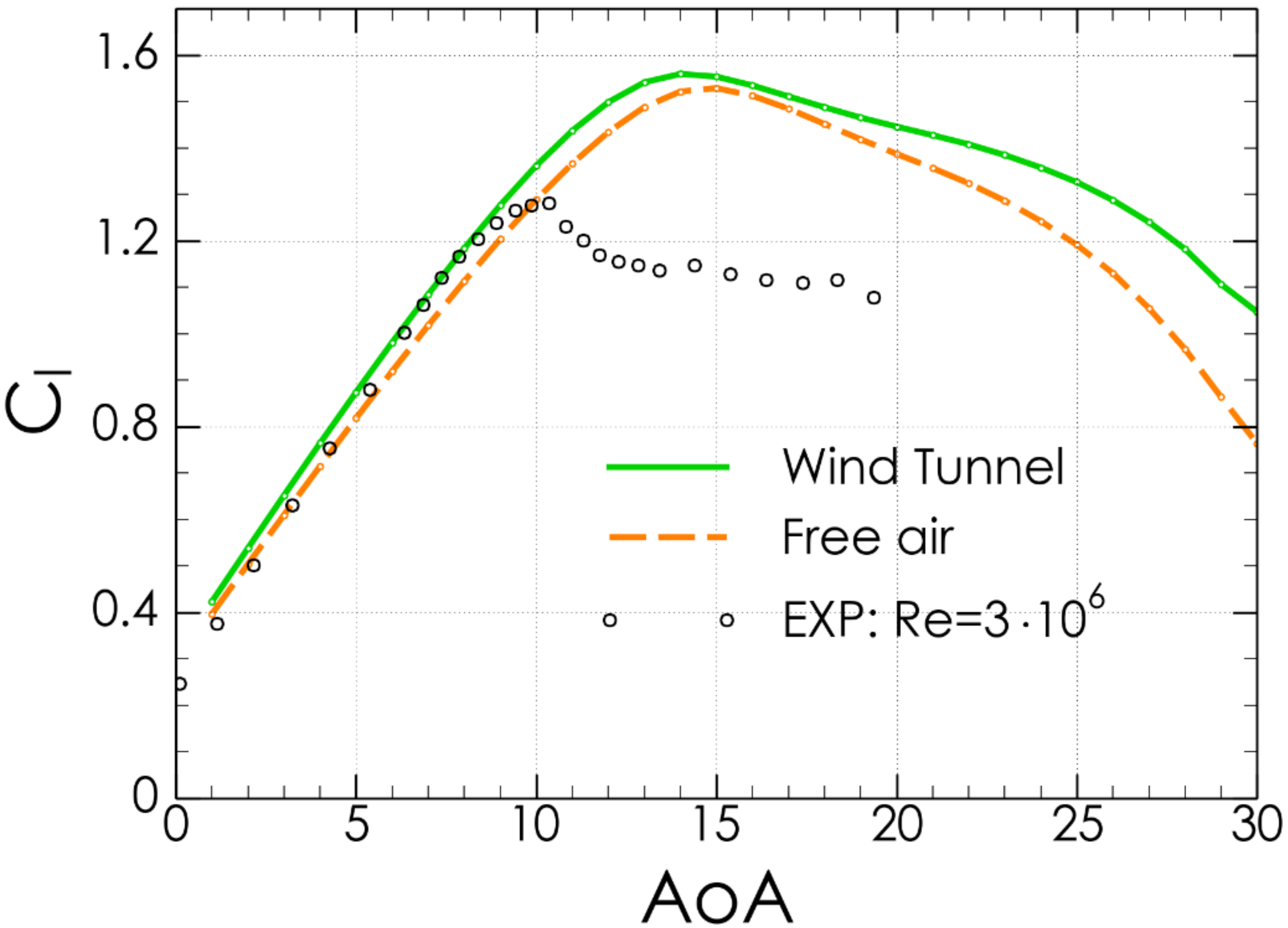


Problem Description

- 2D RANS CFD simulations of wind-turbine airfoils predict substantially too high C_{lmax}
- Even the fairly 'aggressive' SST – especially tuned for separation/stall prediction of aerodynamic devices is too high on high C_{lmax}

SST – Fully Turbulent (FT-tripped), Re=4·10^6

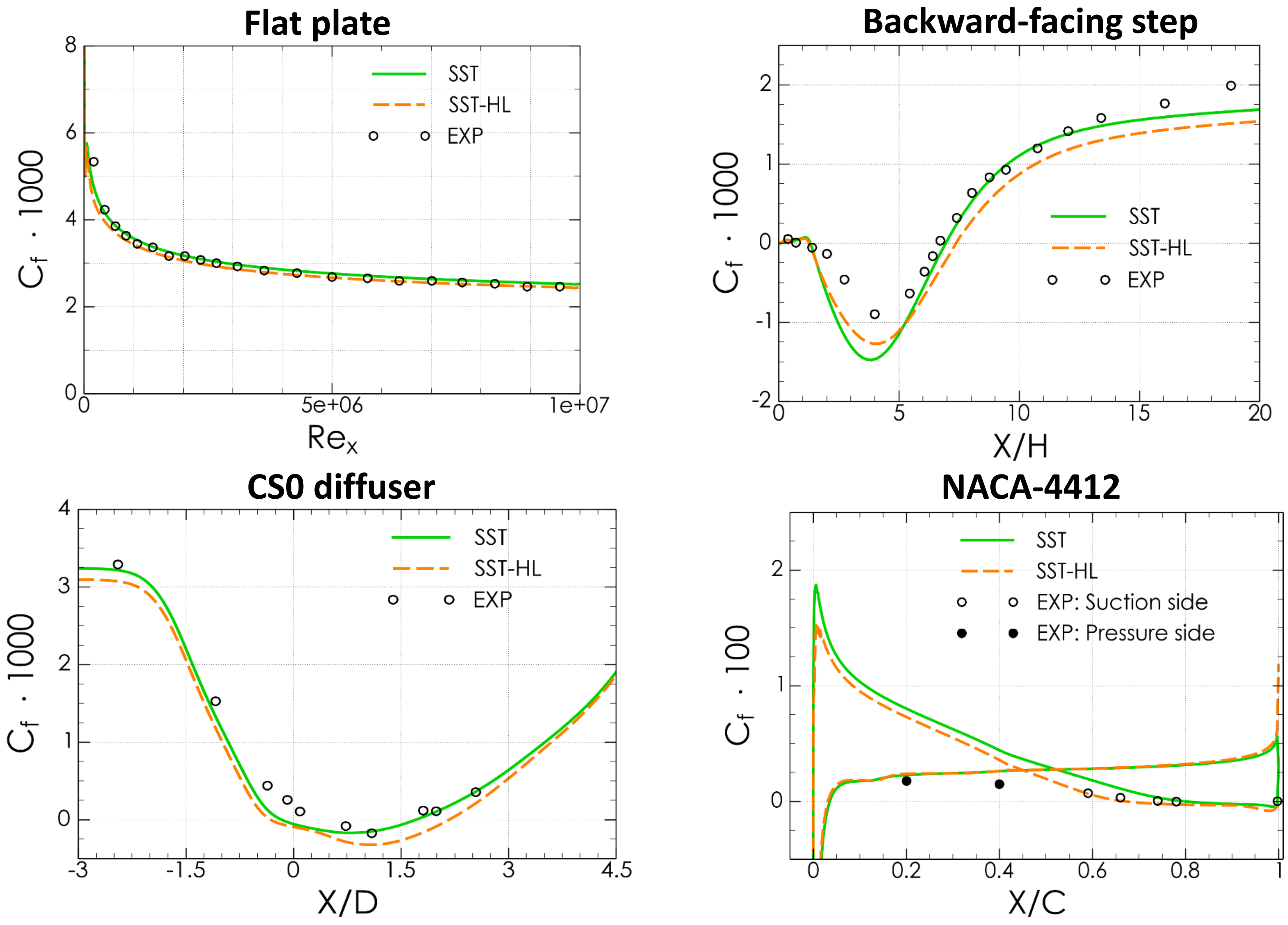


Experiment for DU-96-W-180 airfoil was carried out in the Delft University:

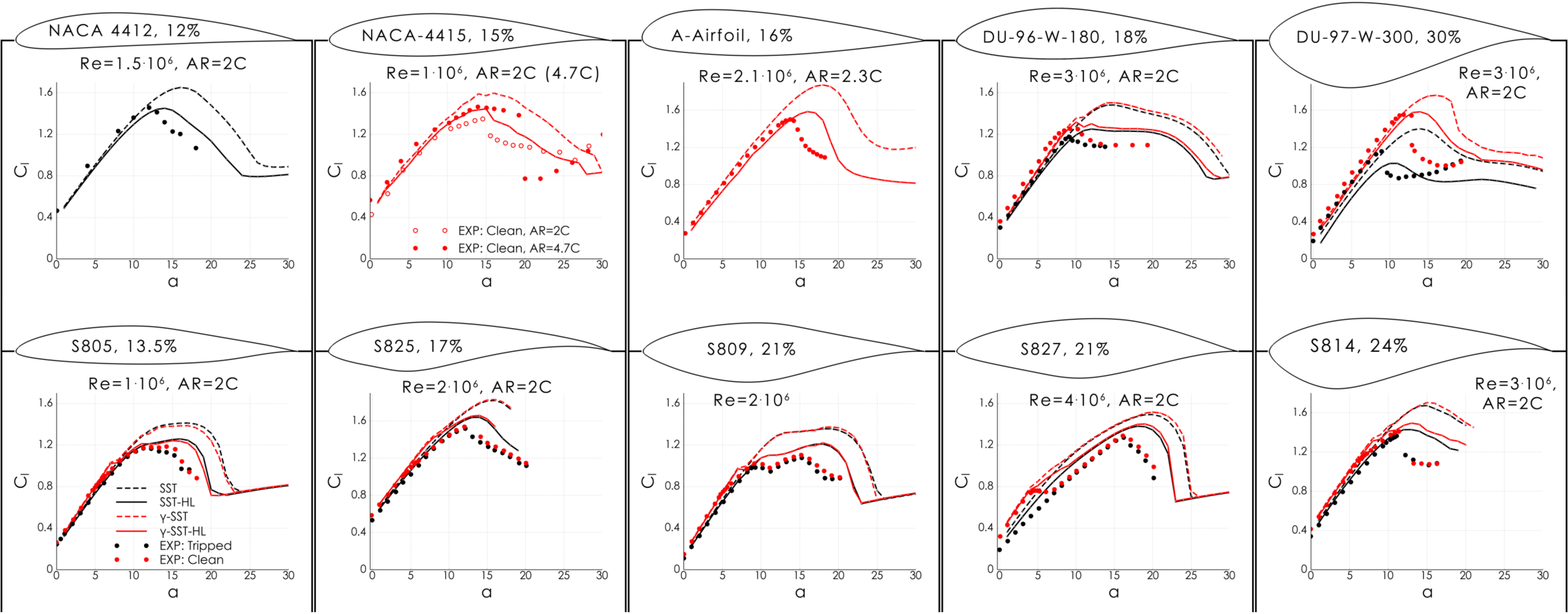
Timmer W. A. & R. P. J. O. M. van Rooij (2003). "Summary of the Delft University Wind Turbine Dedicated Airfoils", AIAA Paper, 2003-0352

Testing of SST-HL model for basic turbulent flows

- SST-HL (High Lift)
  - Allows reduction of a_1 without destroying basic calibration
  - Maintains Flat Plate
  - Produces more separation for Diffuser CS0
  - More separation for NACA 4412 (good or bad?)

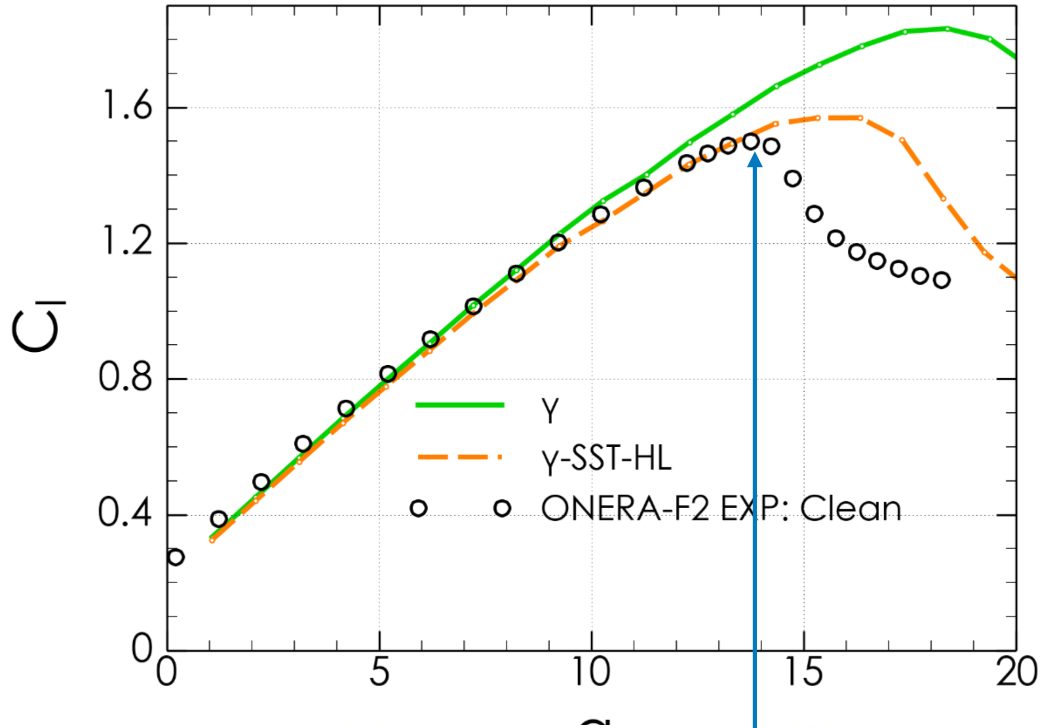


SST and SST-HL models

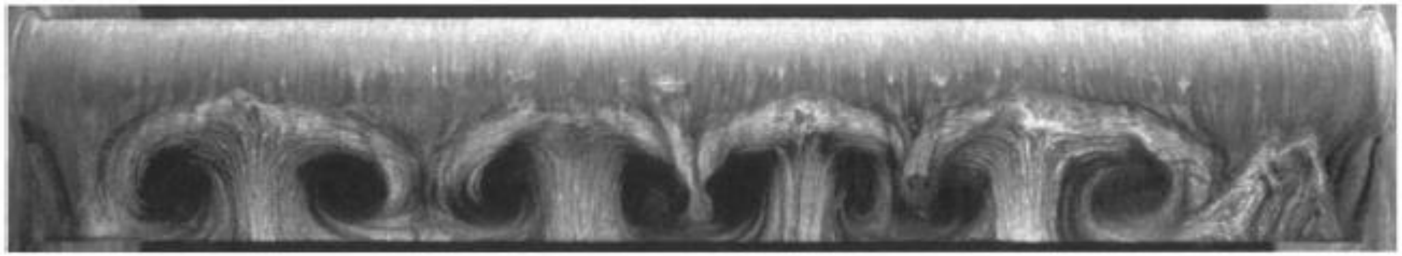


Flow around an A-Airfoil

- Experiment for clean airfoil model was carried out in the F2-ONERA wind tunnel at $Re=2.1 \cdot 10^6$ and $M \approx 0.15$
- Preliminary CFD results indicates that laminar-turbulent transition has a big impact on the airfoil characteristics
- Therefore current numerical investigations are carried out using transition models
  - Intermittency-SST model (γ-SST)
  - Intermittency-SST model with HL correction (γ-SST-HL)
- Computational domain is based on the experimental wind tunnel



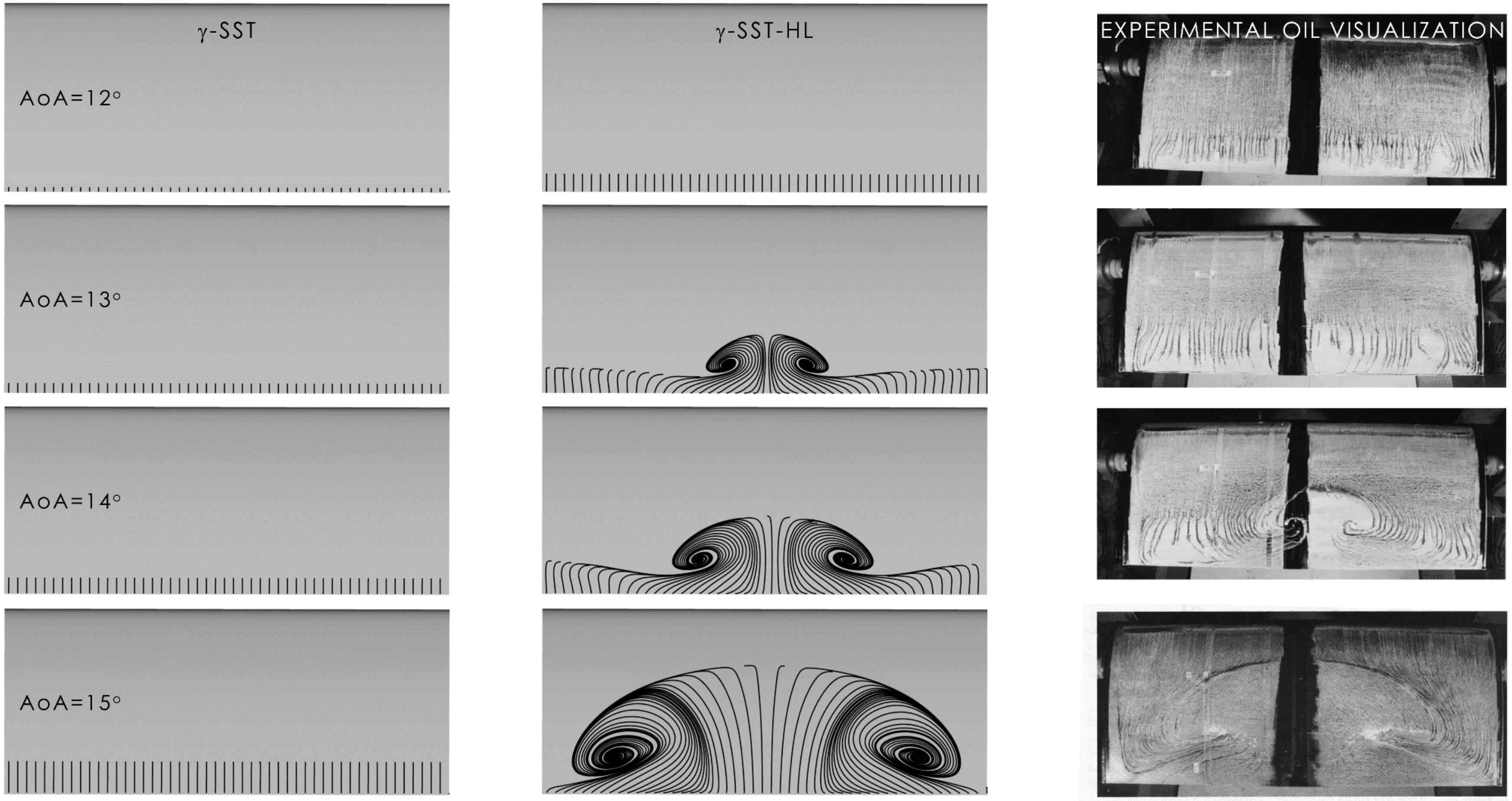
G. Schewe / J. Wind Eng. Ind. Aerodyn. 89 (2001) 1267–1289 1283



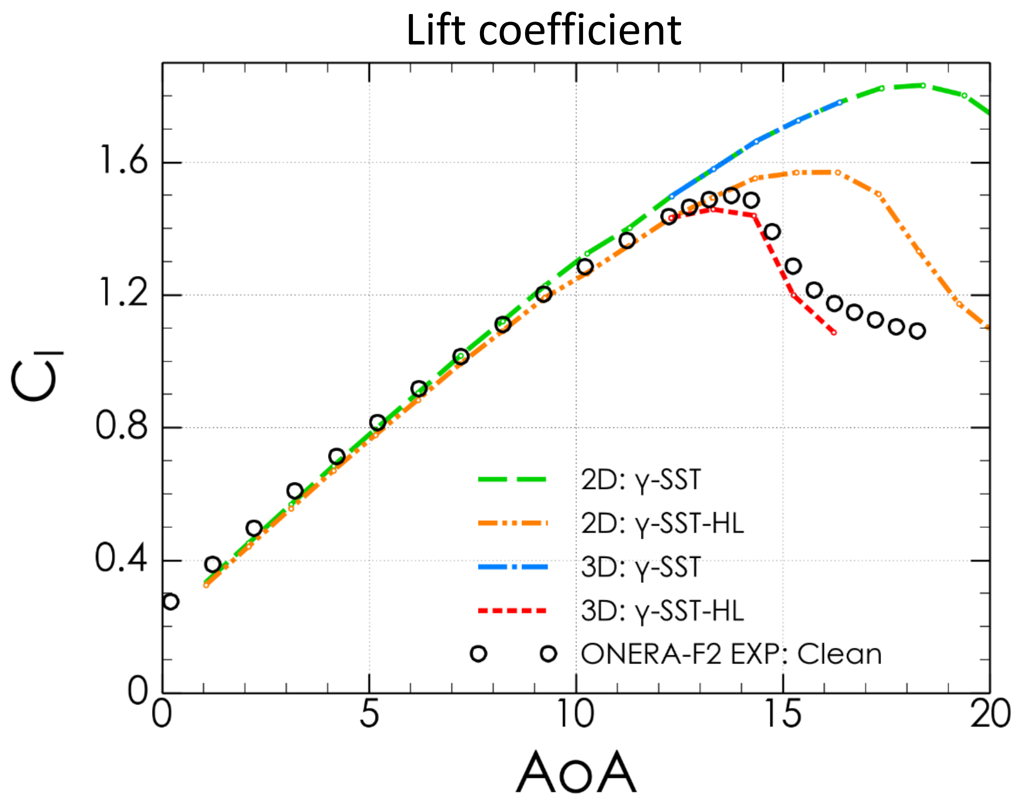
$Re = 7.4 \times 10^5$ $C_D = 0.11$ $C_L = 1.1$

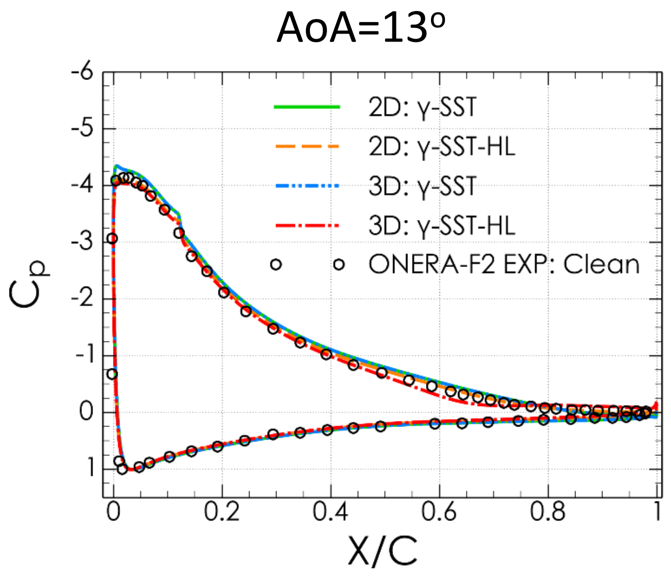
3D Simulations - Flow Structure

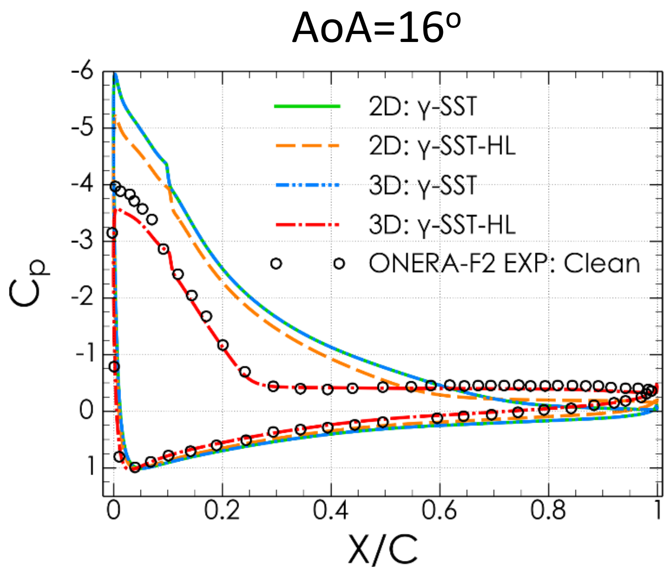
- Wind tunnel (L_z=2.3C) without sidewall BL account
  - Symmetry boundary conditions in spanwise direction are used for slip wall imitation
  - Incompressible flow, Re = $2.1 \cdot 10^6$, α = 12^o-16^o
- Computational mesh is based on the 2D mesh extruded in spanwise direction with uniform grid step (80 cells in Z direction)
  - Total mesh size is about 10M cells



Airfoil characteristics at midspan section



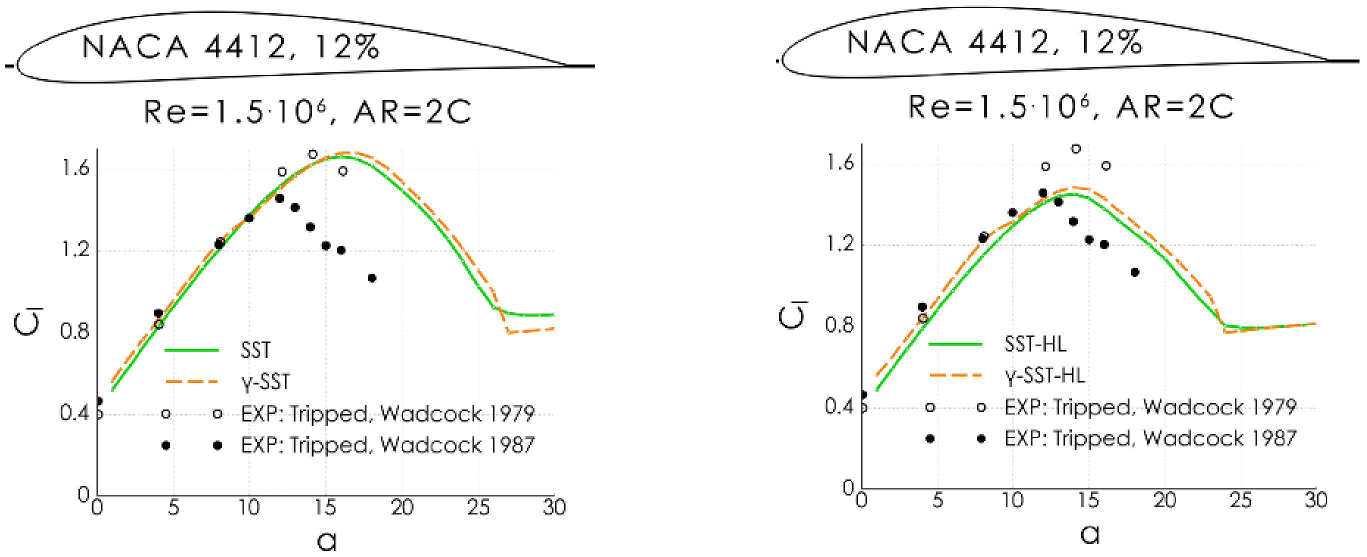


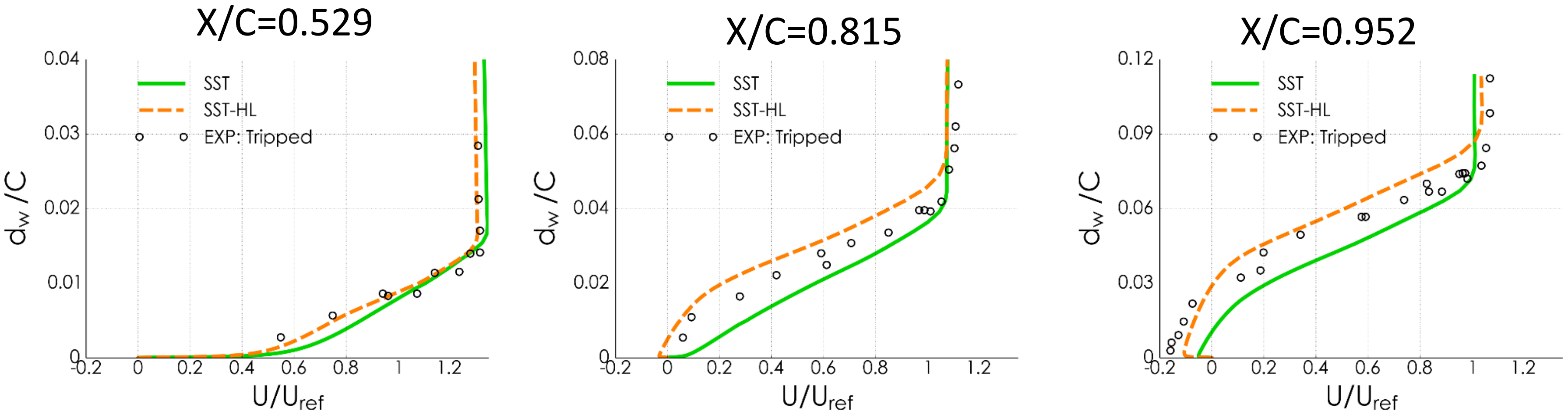


- γ-SST model delays appearance of 3D structures which leads to an overprediction of lift coefficient
- γ-SST-HL model fits experimental data (lift and pressure coefficient) well in the 3D wind tunnel setup

Streamwise velocity profiles at AoA=12^o

- When looking at a number of airfoil cases it seems we need to re-calibrate RANS models to be more aggressive on separation
- Need to replace NACA 4412 (1979) data with (1987) data
- Would such a model be overly aggressive on shock-BL cases?
- Free parameter a_1 helpful, as models need to be adjusted to flow types





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BSL2 Turbulence Models

- Develop two-equation model framework with tunable coefficients
  - In the past – model coefficients have been exposed – however they are inter-related and any non-expert change will lead to deterioration of basic flows (flat plate)
  - We have a range of scale equations (k-ω, BSL/SST, k-ε, RKE, V2F)
    - To allow users to select a suitable model for their application
    - Very expensive as each model needs to be developed/combined with
      - Y+ - insensitive wall, rough wall, transition, CC, buoyancy, DES/SBES, ….
    - Wouldn't it be better to have 1 scale equation which can be tuned over a wide range of the parameter space.
  - BSL2 will have several free coefficients which do not affect basic flows

BSL2 model formulation

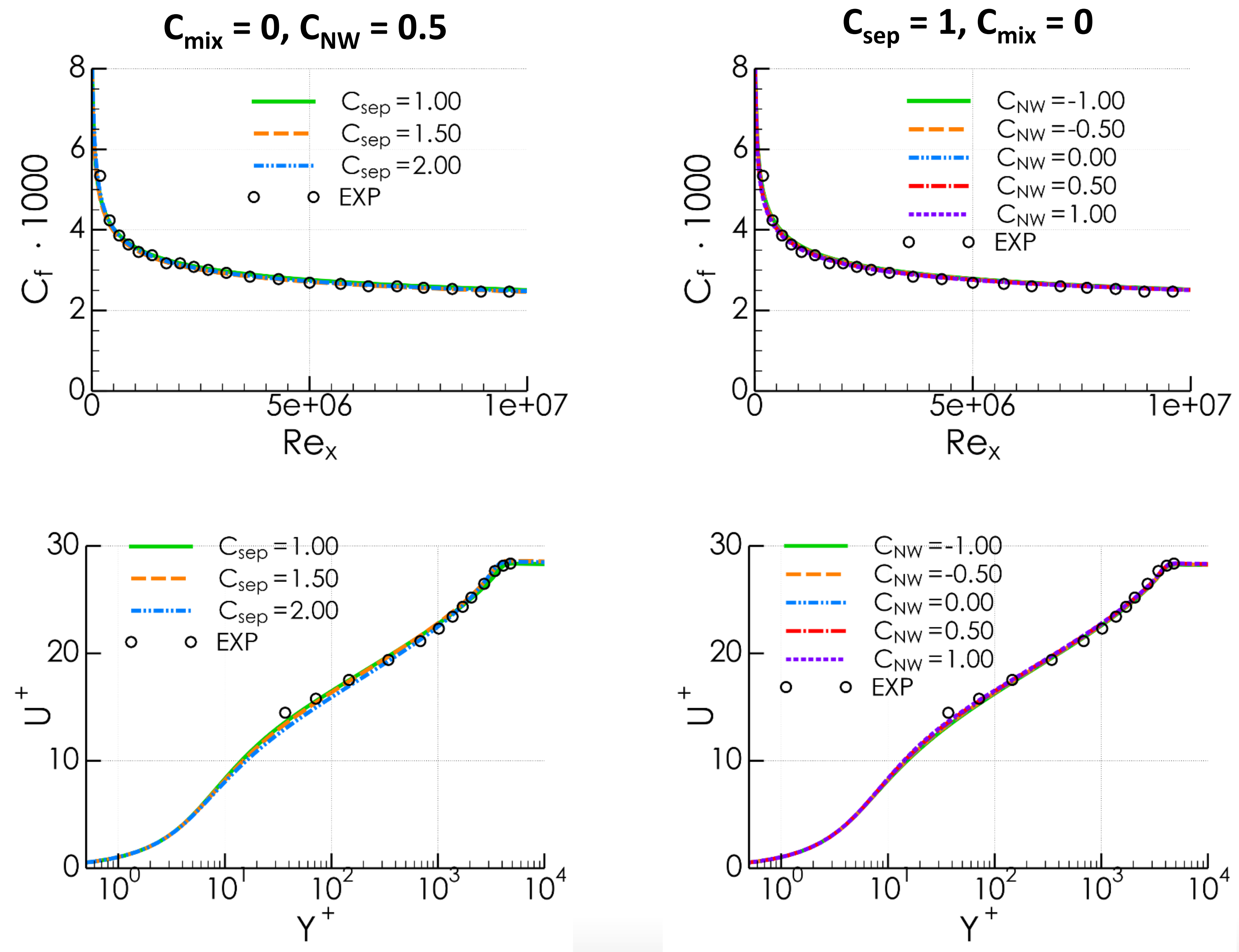
- BSL2 will have several free coefficients which do not affect basic flows:
  - C_{SEP} - allow to steer separation
  - C_{NW} - allow to calibrate near wall behavior
  - C_{MIX} - alow to calibrate free shear flows independently from wall boundary layers

$$\frac{\partial(\rho k)}{\partial t} + \frac{\partial(\rho k U_j)}{\partial x_j} = P_k - C_\mu \rho k \omega + \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right]$$

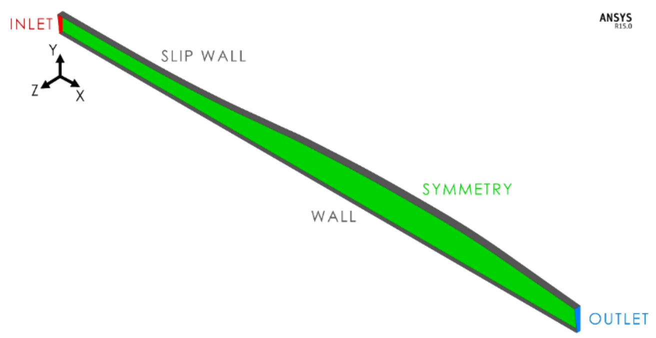
$$\frac{\partial(\rho \omega)}{\partial t} + \frac{\partial(\rho \omega U_j)}{\partial x_j} = C_{\omega 1}\frac{\omega}{k}P_k - C_{\omega 2}\rho\omega^2 + \rho C_{\omega 3}\frac{2}{\sigma_\omega \omega}\frac{\partial k}{\partial x_j}\frac{\partial \omega}{\partial x_j} + \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_\omega}\right)\frac{\partial \omega}{\partial x_j}\right]$$

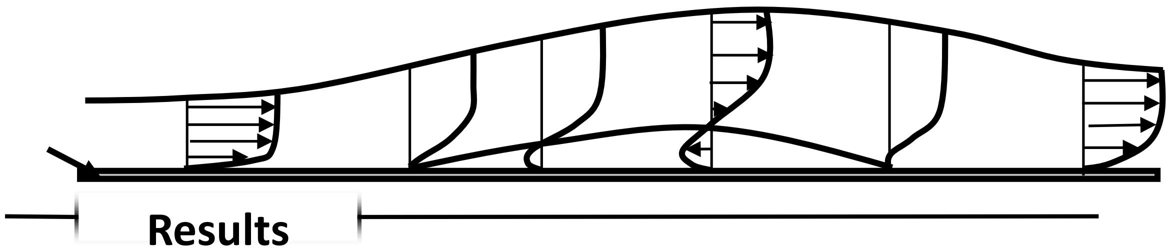
Flat Plate Boundary Layer

- Incompressible flow
  - Re = 10^7
- Model maintains calibration for wide range of coefficient changes

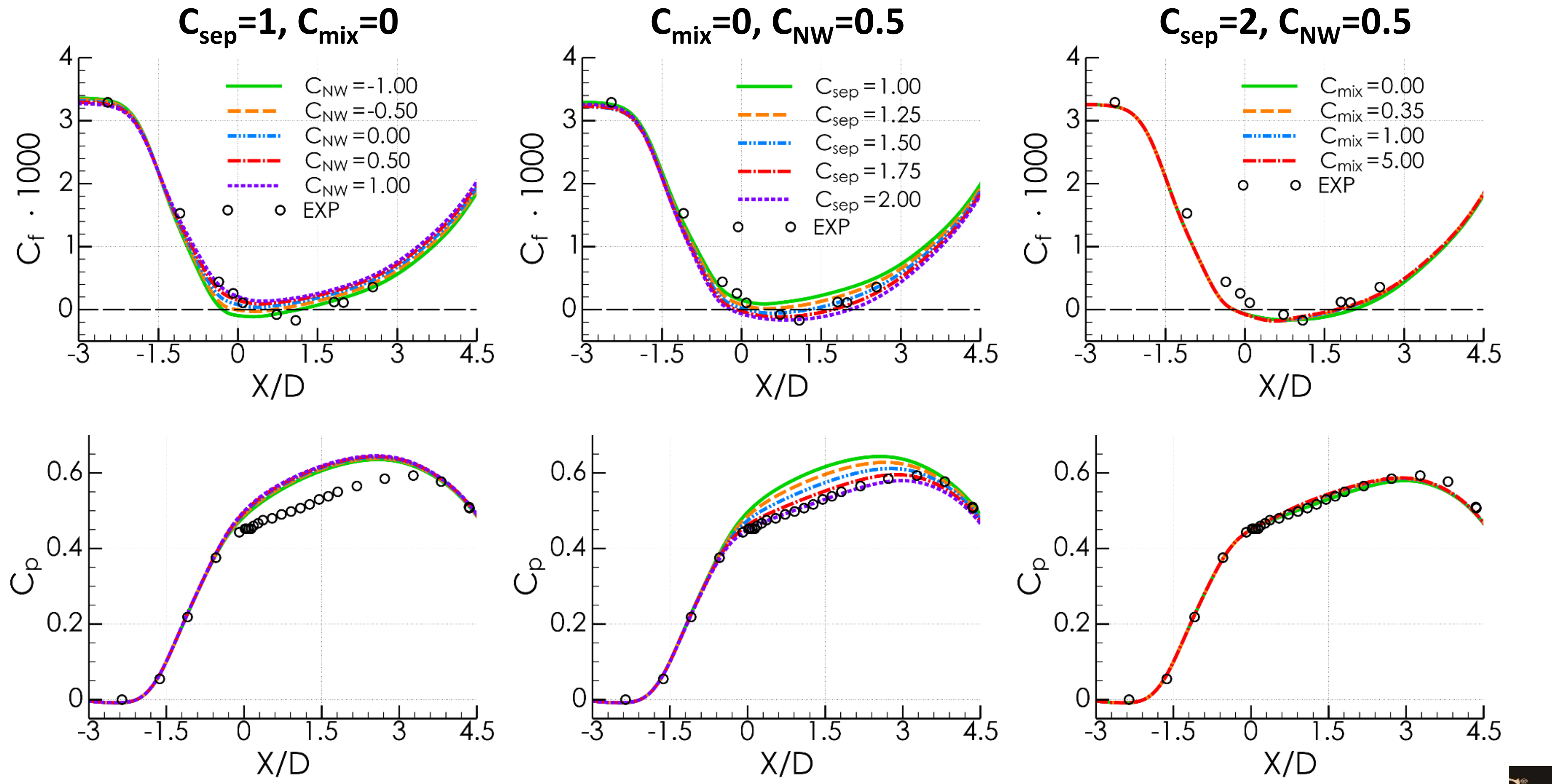


Diffuser Flows: CS0 Diffuser



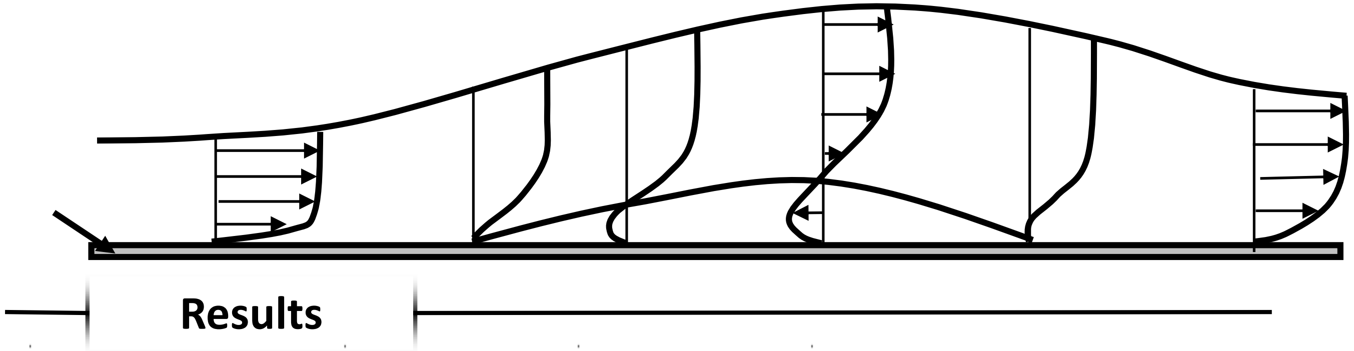


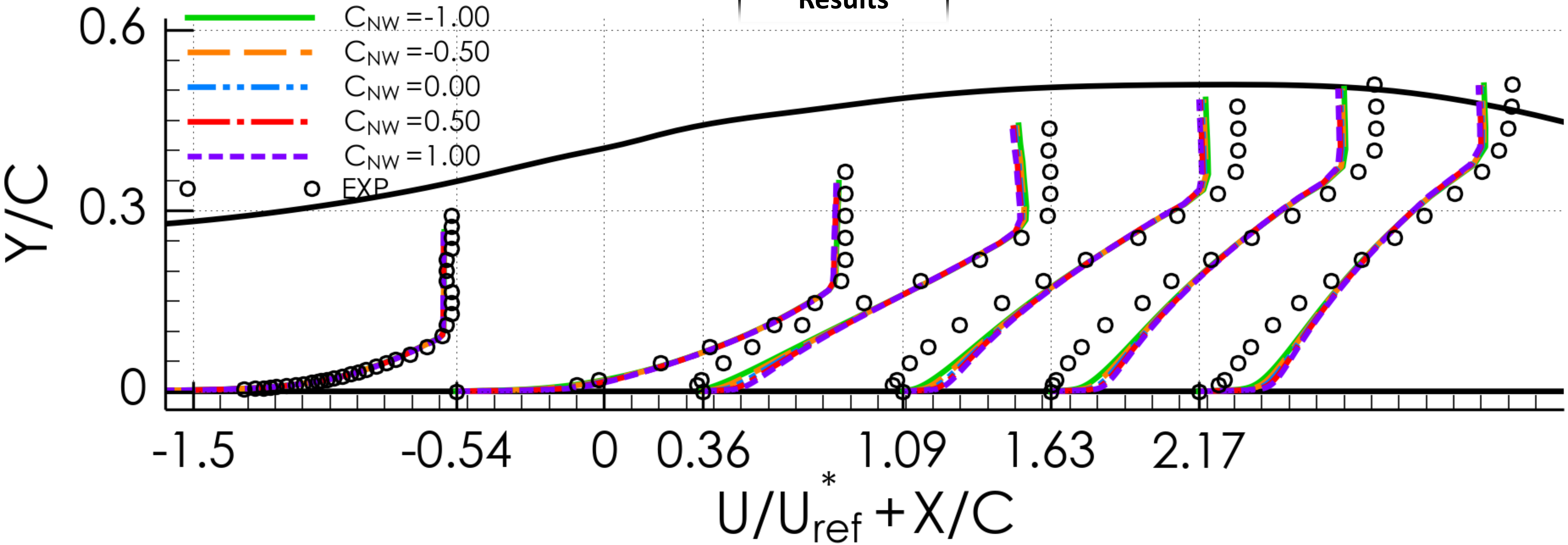
Results



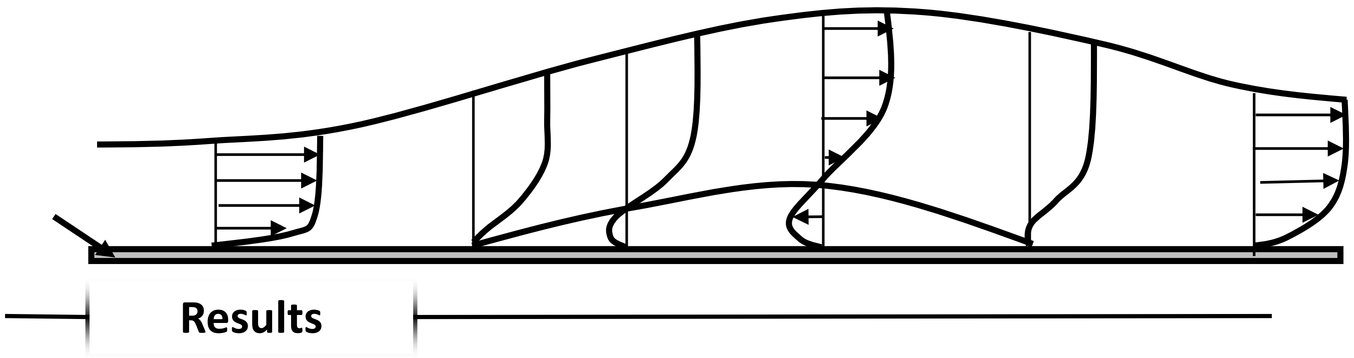
- Incompressible flow
  - Re = 10^5
- Boundary conditions
  - Inlet
    - Inlet boundary with uniform velocity and turbulence properties
  - Wall
    - No-slip wall boundary condition
  - Slip wall
    - The experimentally measured location of a streamline is used as an external boundary with the free slip wall boundary condition

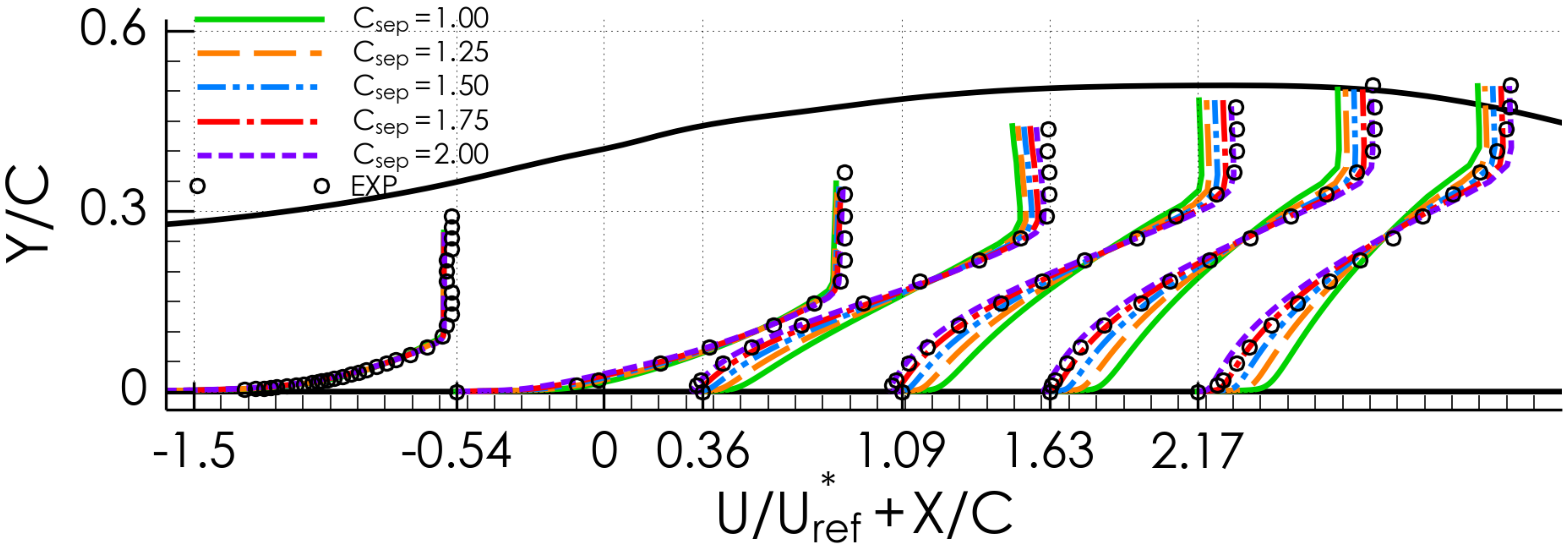
CS0 Diffuser (Driver NASA): C_{sep}=1, C_{mix}=0



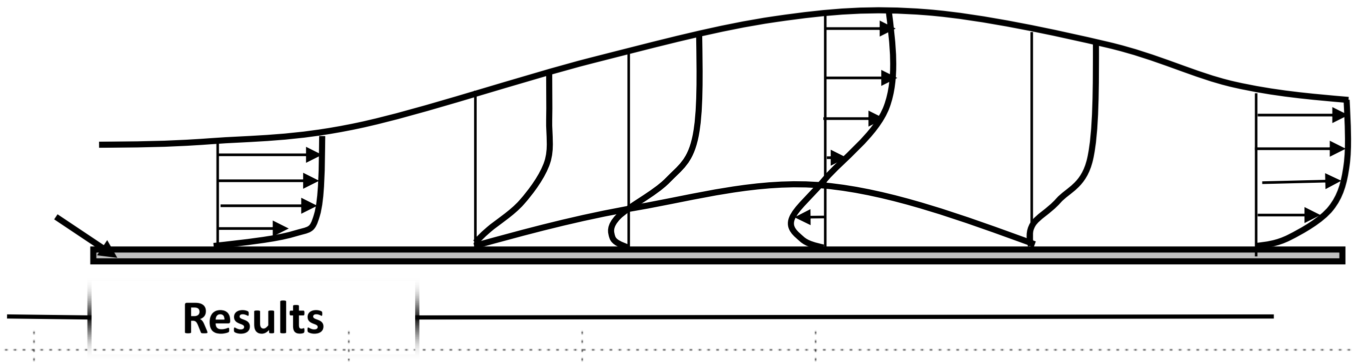


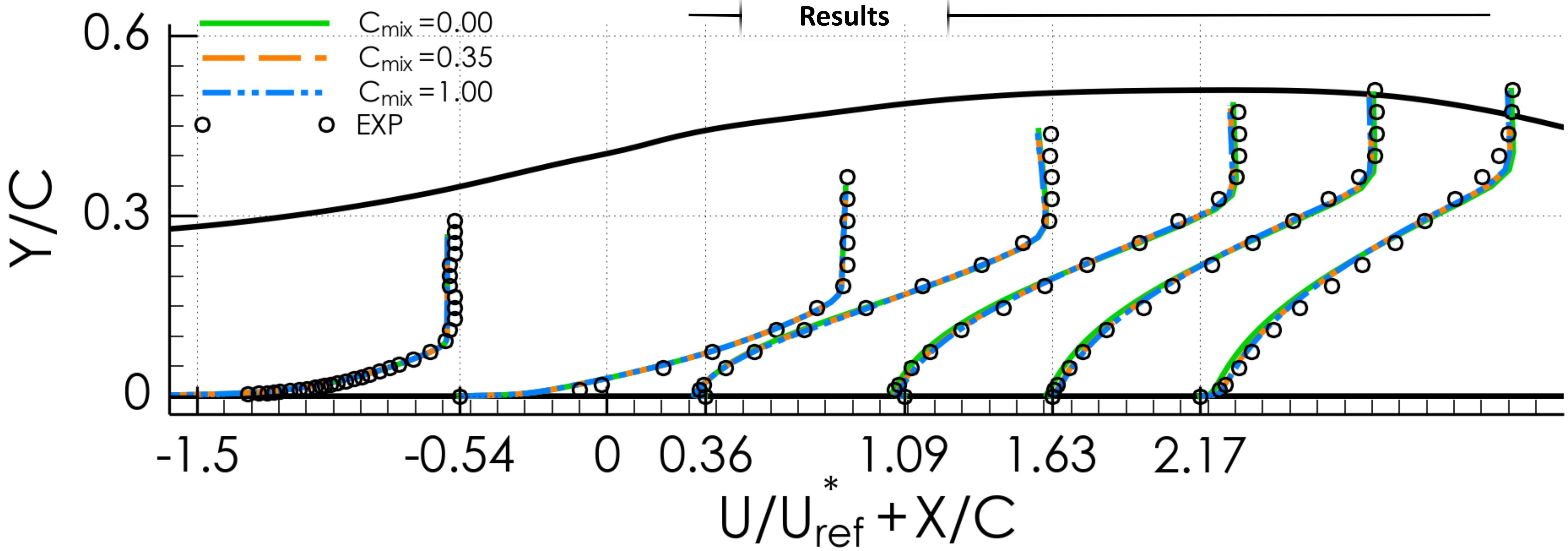
CS0 Diffuser: C_{mix}=0, C_{NW}=0.5



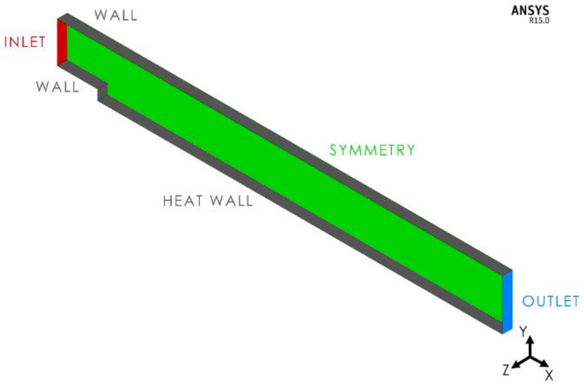


CS0 Diffuser: C_{sep}=2, C_{NW}=0.5





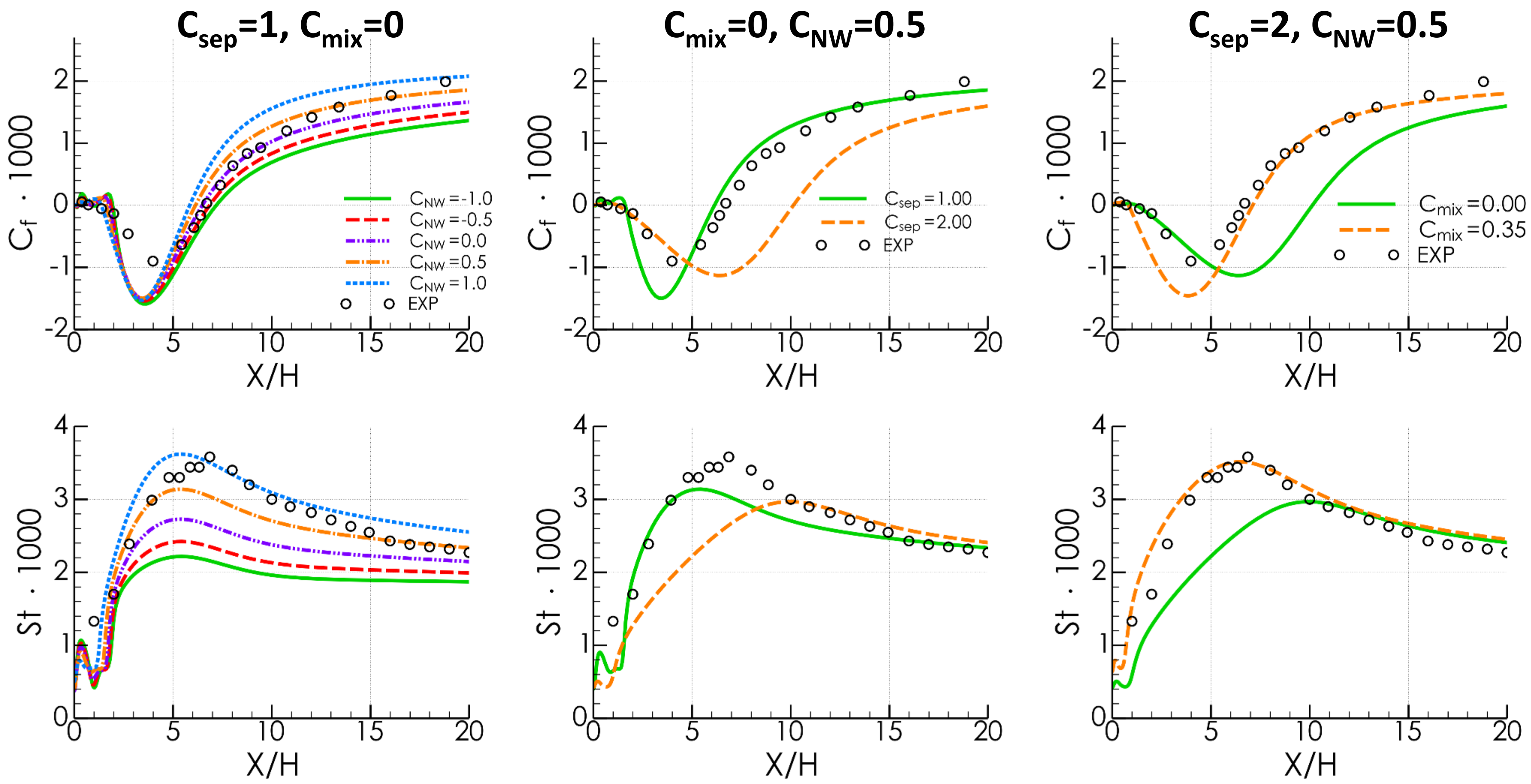
Backward-Facing Step



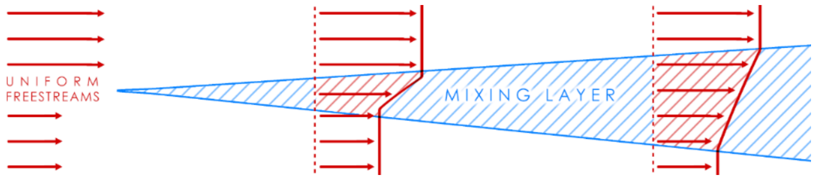
C_{sep} ↑ => Length of separation ↑

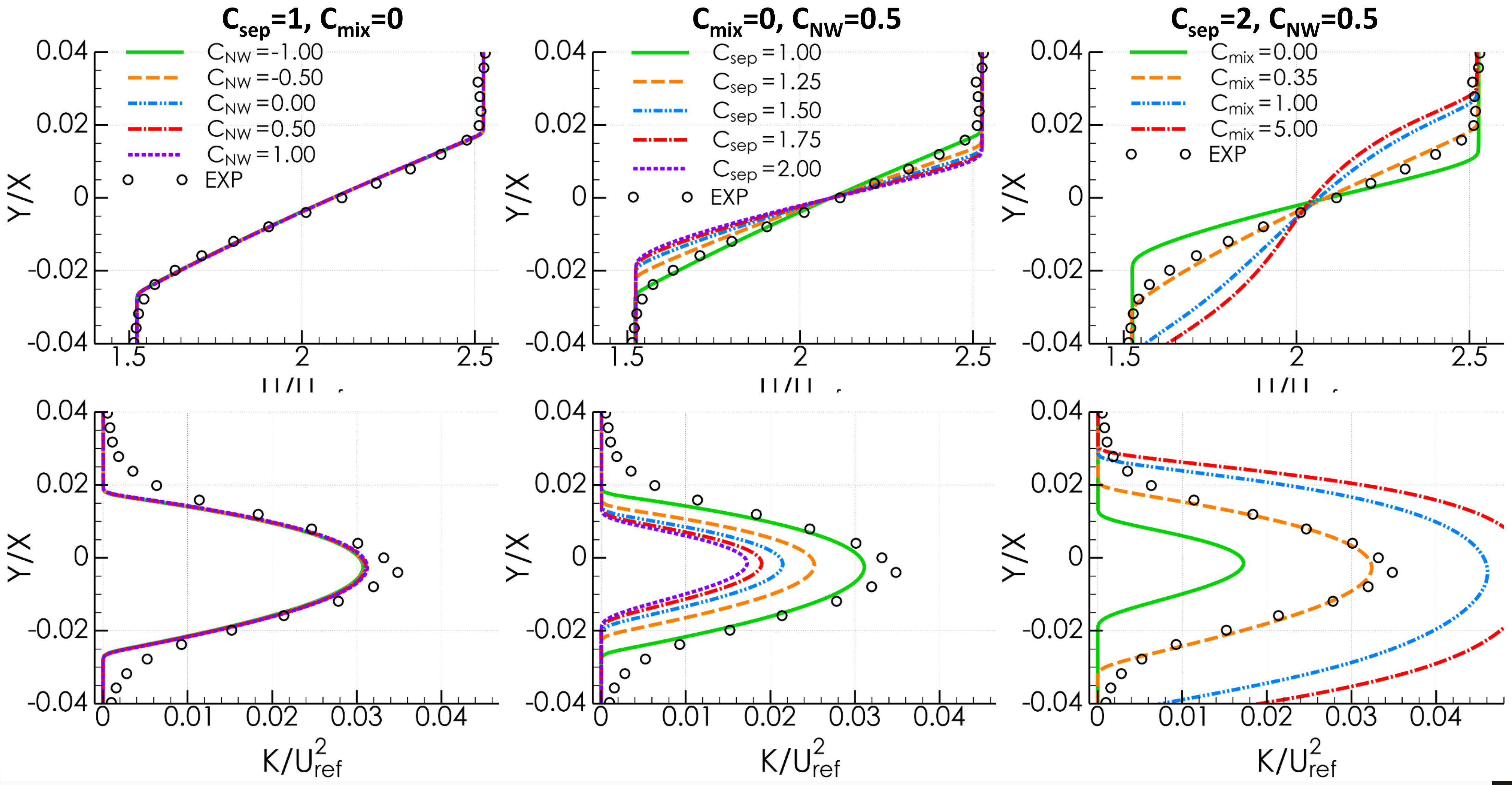
C_{mix} ↑ => Spreading rate of mixing layer ↑ => Reattachment accelerates

- Incompressible flow
  - Re = $2.8 \cdot 10^4$
- Boundary conditions
  - Inlet
    - Inlet boundary with specified velocity and turbulence properties
  - Wall
    - No-slip adiabatic wall boundary condition (heat flux = 0)
  - Heat wall
    - No-slip wall boundary condition with specified heat flux, q = 270 [W/m]



Mixing Layer





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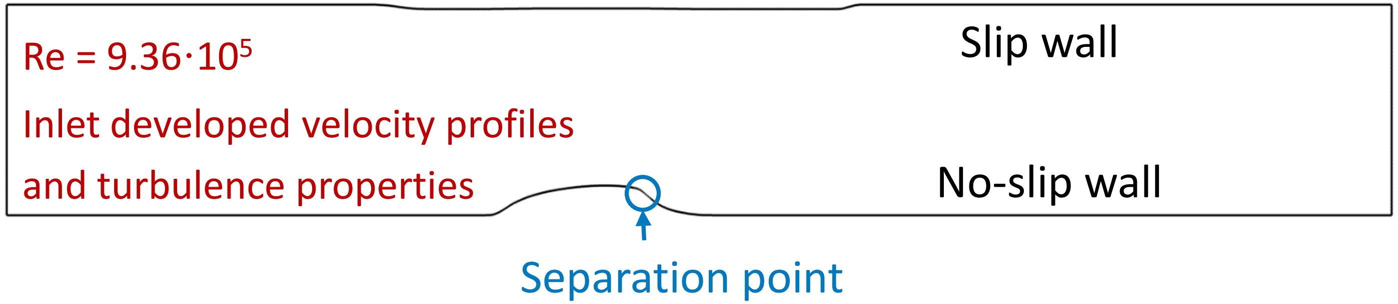
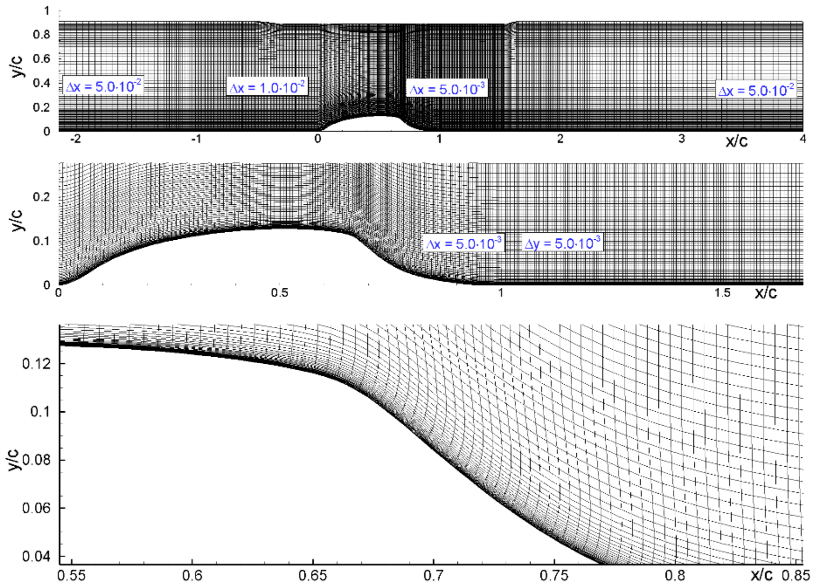
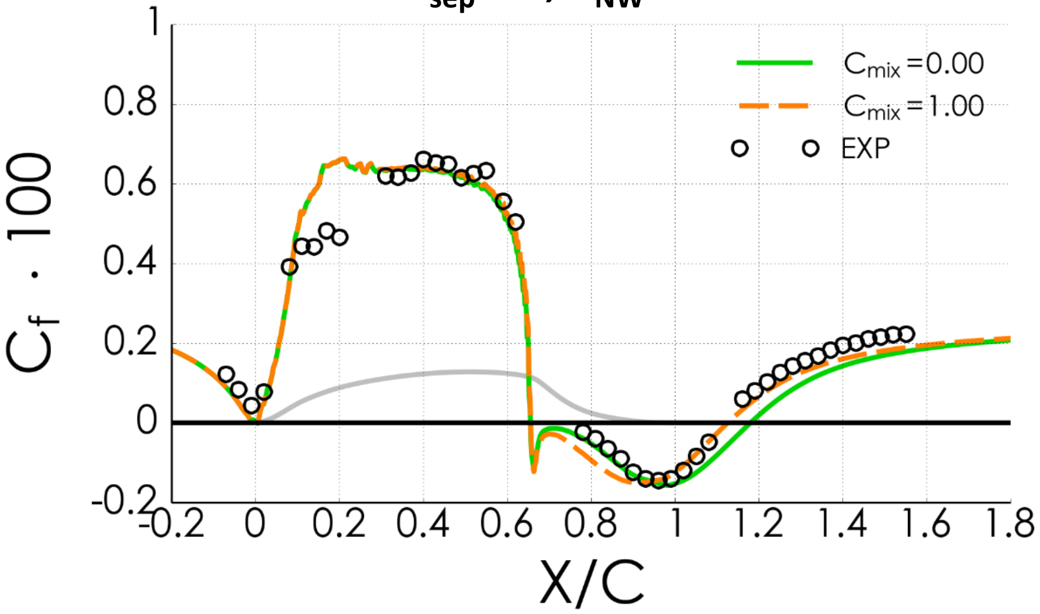
Mixing Layers: Hump

Incompressible flow

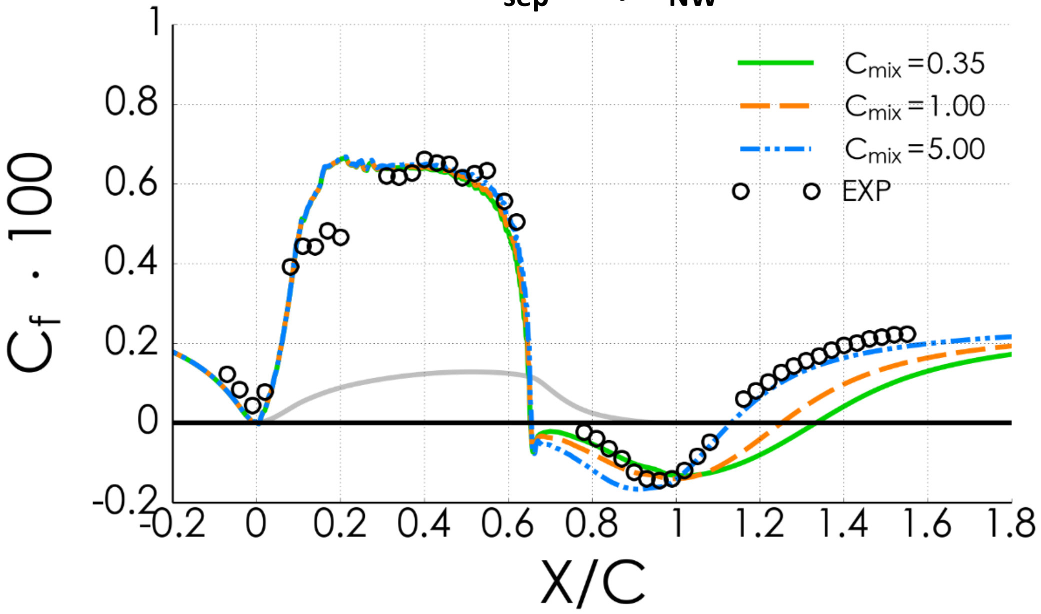




C_{sep} = 1, C_{NW}=0.5



C_{sep} = 2, C_{NW}=0.5



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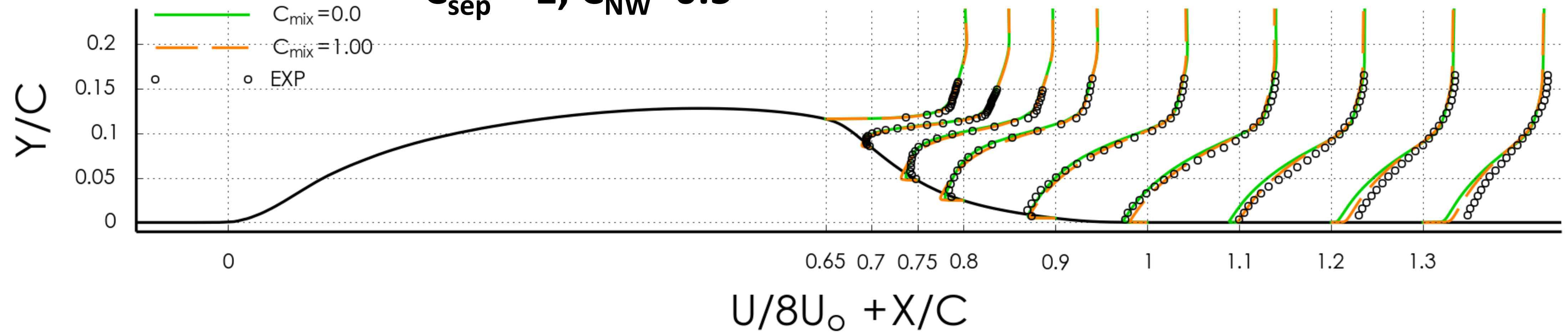
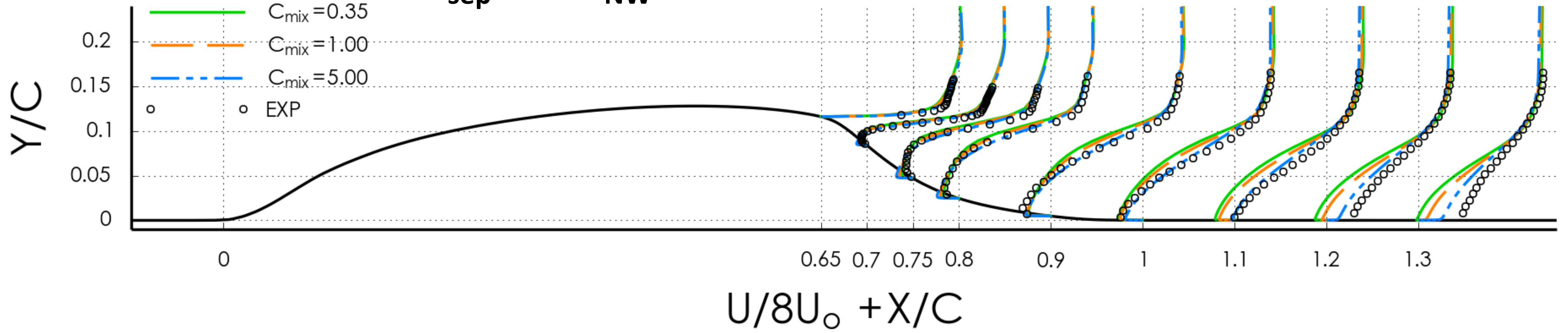
Hump Flow: Velocity Profiles

C_{sep} = 1, C_{NW}=0.5



C_{sep} = 2, C_{NW}=0.5



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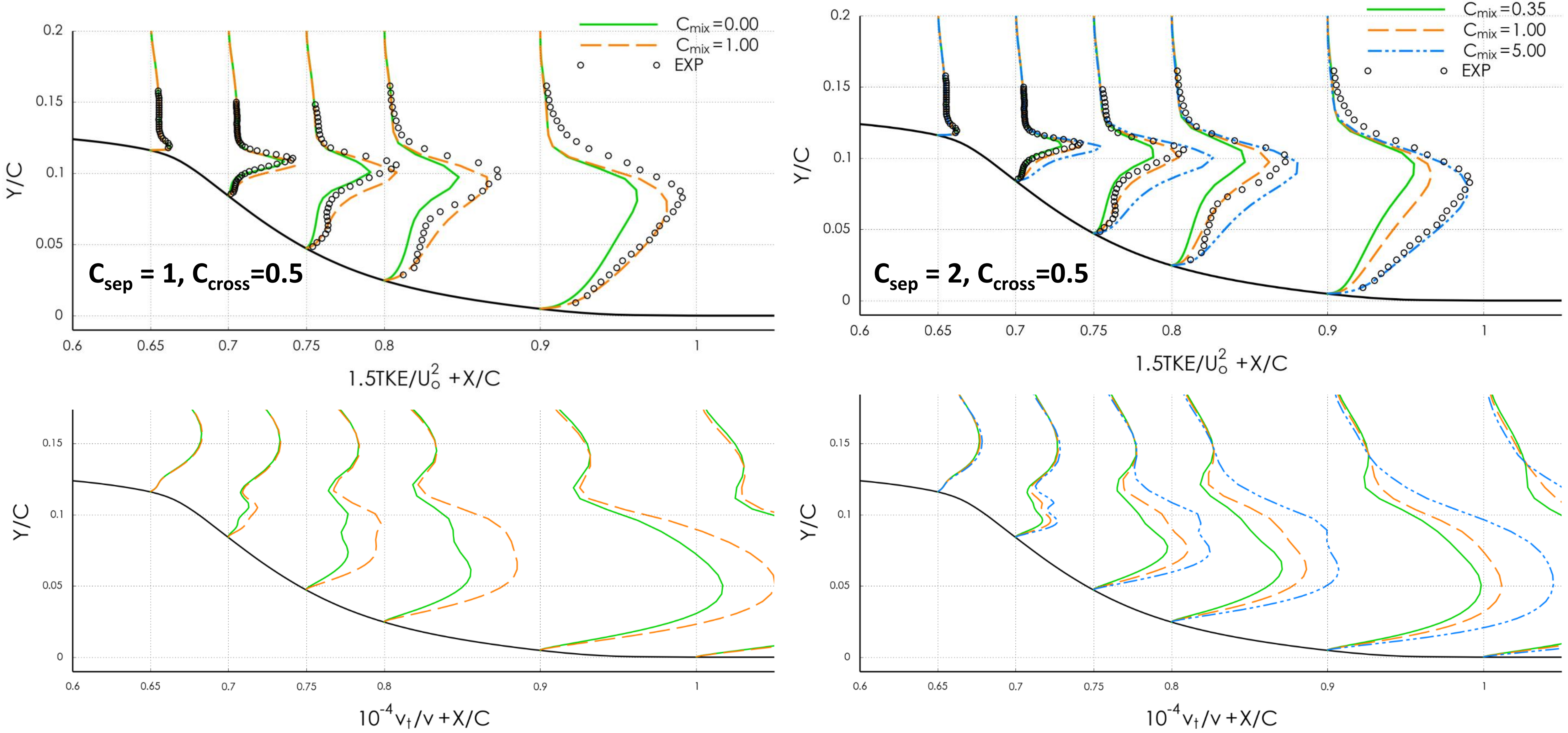
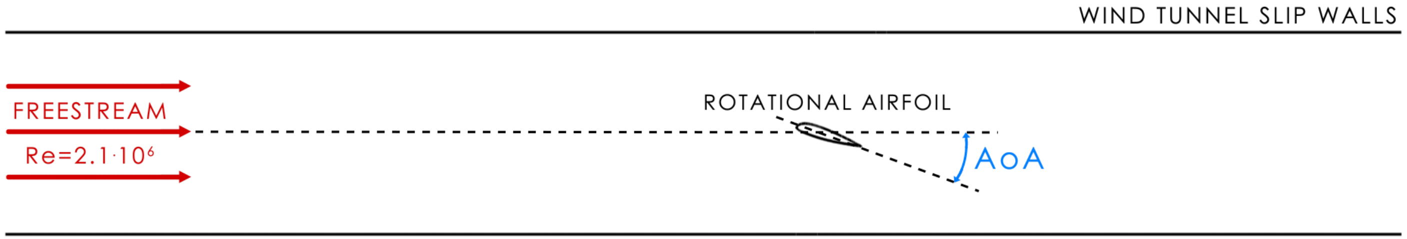
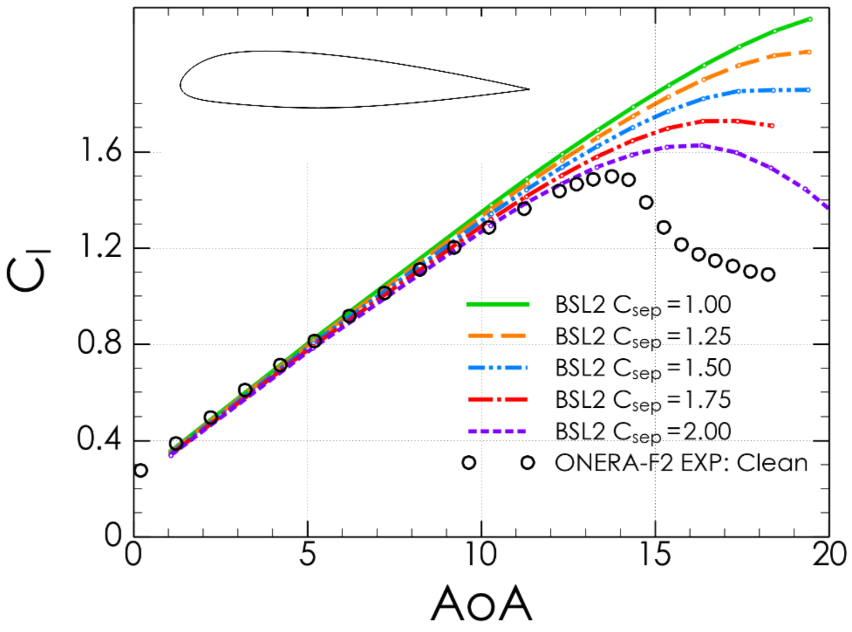
Turbulence Kinetic Energy and Eddy Viscosity Ratio

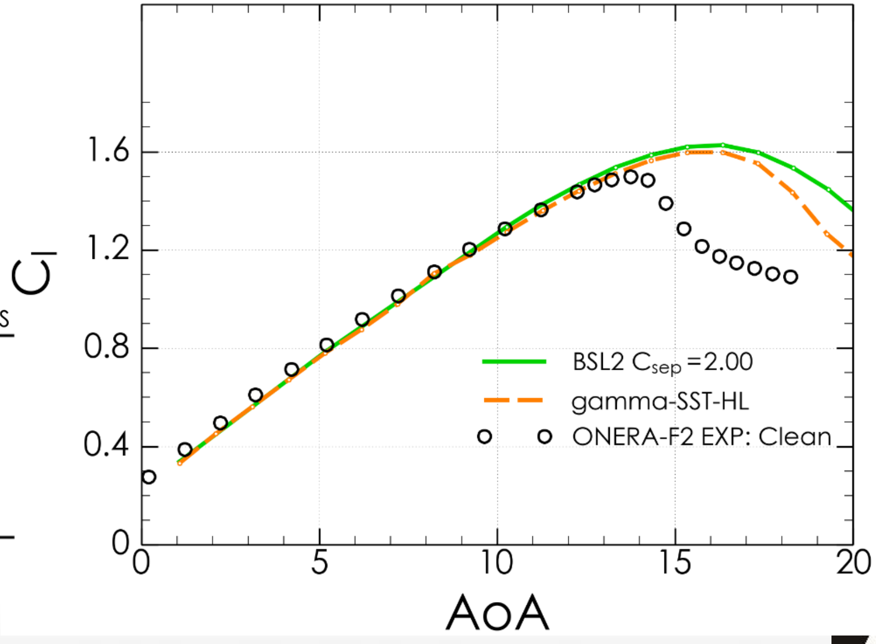


Aerodynamic Flows: A-Airfoil - C_{Sep}

- Incompressible flow
  - $Re = U_\infty \cdot C/\nu = 2.1 \cdot 10^6$
  - $\alpha = 0^o - 20^o$
- The size of computational domains corresponds wind tunnel parameters
- Boundary conditions
  - Uniform freestream is specified at the inlet
    - $Tu = 0.1\%$, $\nu_t/\nu = 1$
  - Constant pressure is specified at the outlet boundary
  - Non-slip walls are specified on the airfoil surface
  - Slip walls is specified on top and bottom tunnel walls







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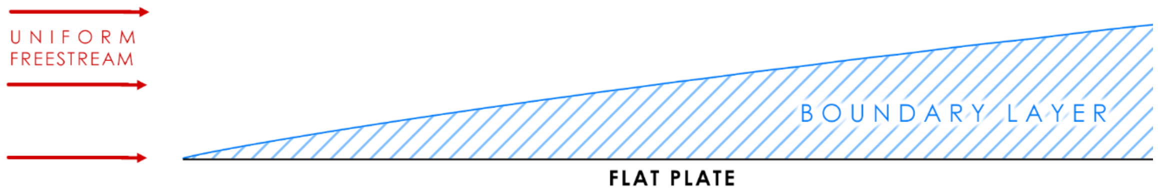
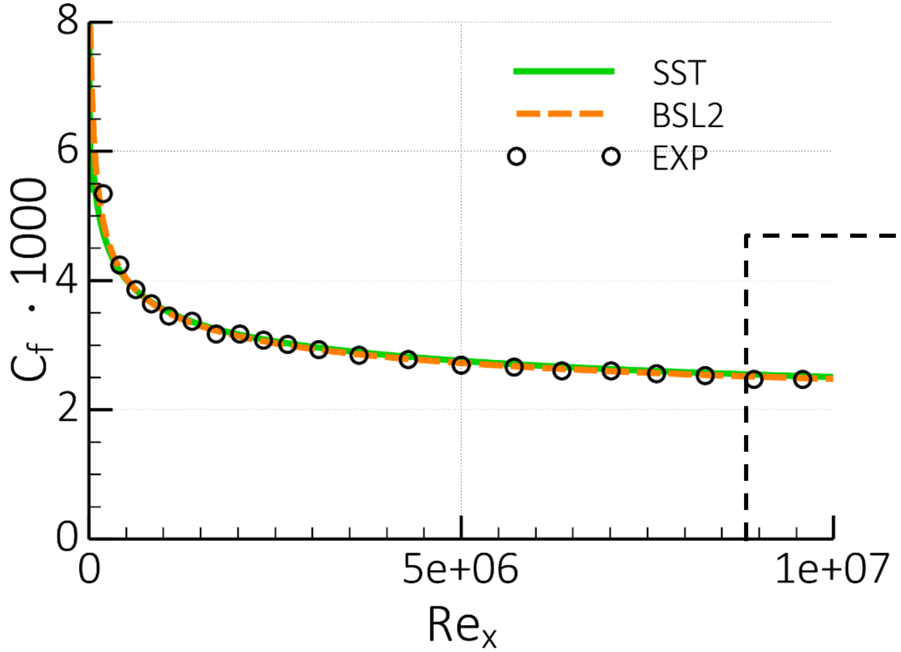
Zero Pressure Flat plate Boundary Layer

- Incompressible flow
- $Re = U_{ref} \cdot L/\nu = 10^7$
  - L = 5 [m] length of the flat plate
  - U_{ref} = 10 [m/s] uniform freestream velocity

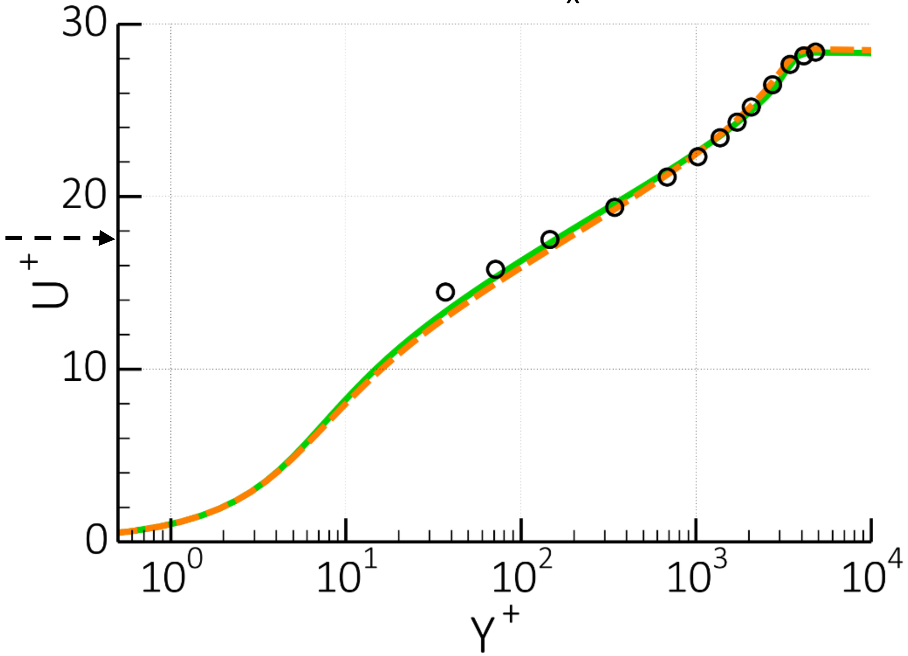
Flow scheme



Skin friction coefficient



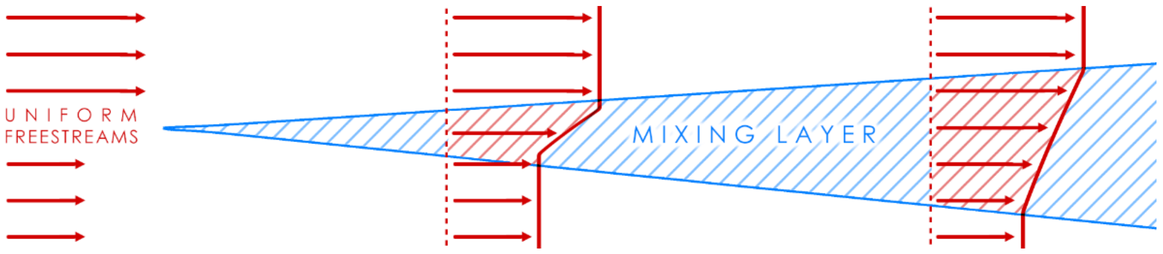
Velocity profile at $Re_x = 8.774 \cdot 10^6$



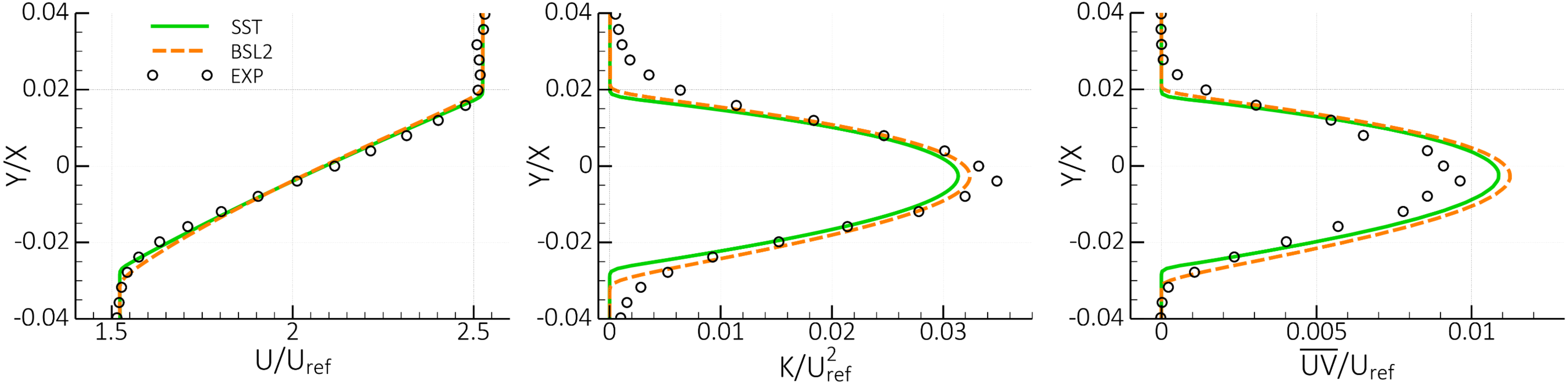
Mixing Layer

- Incompressible flow
  - U_{ref} = 6 [m/s]
  - ρ = 1.185 [kg m^{-3}]

Flow scheme

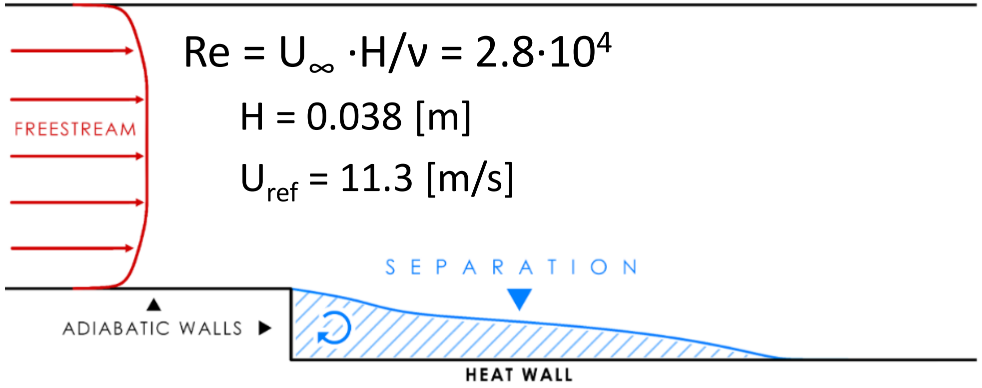


Prediction quality is almost identical for all the measurements planes

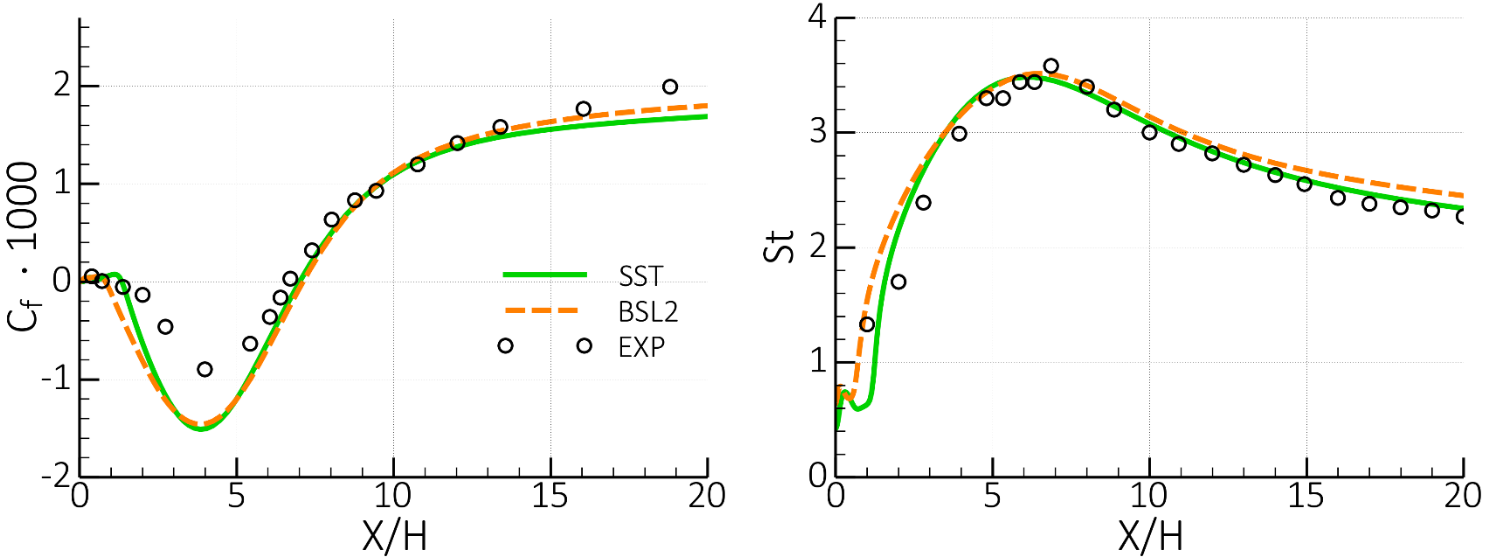


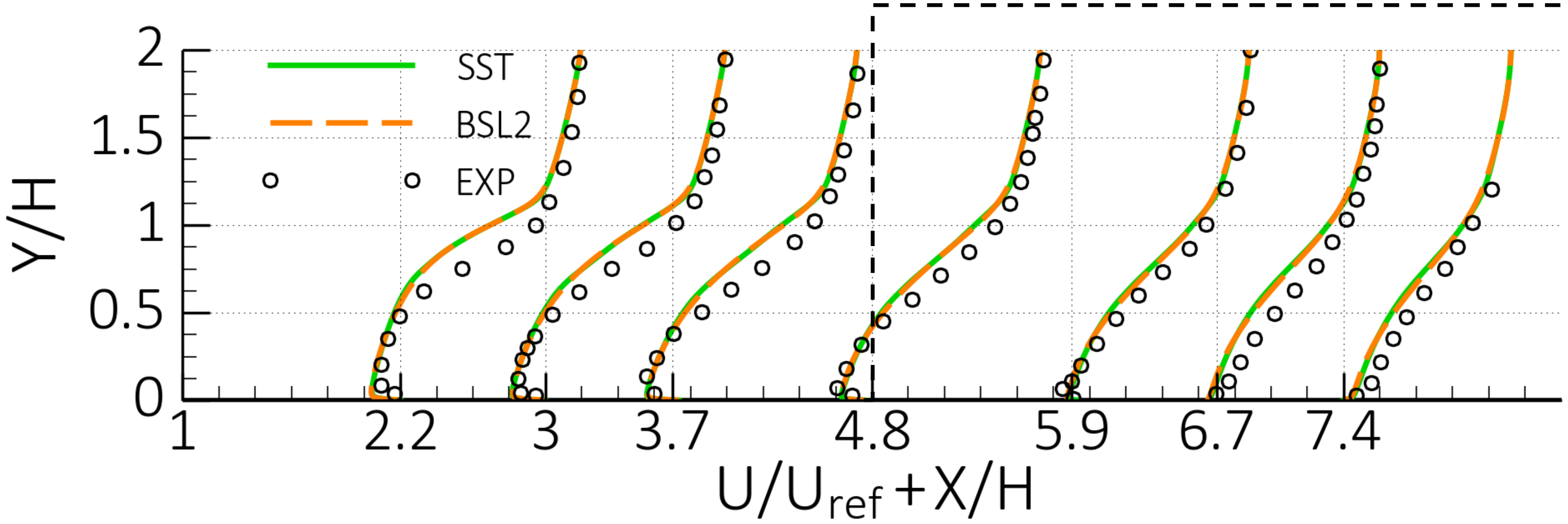
Backward-Facing Step

Flow scheme

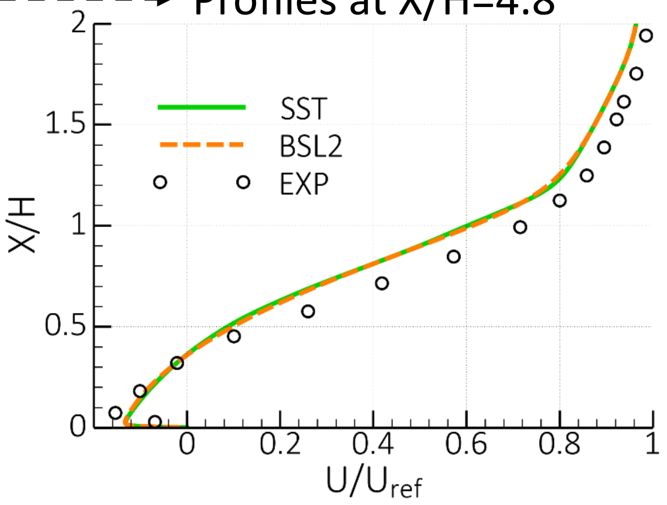


Skin friction coefficient and Stanton number on the heat wall



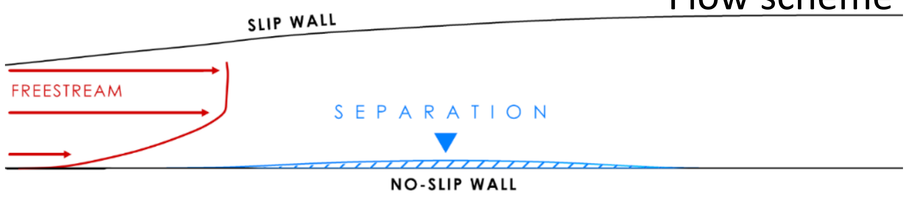


Profiles at X/H=4.8



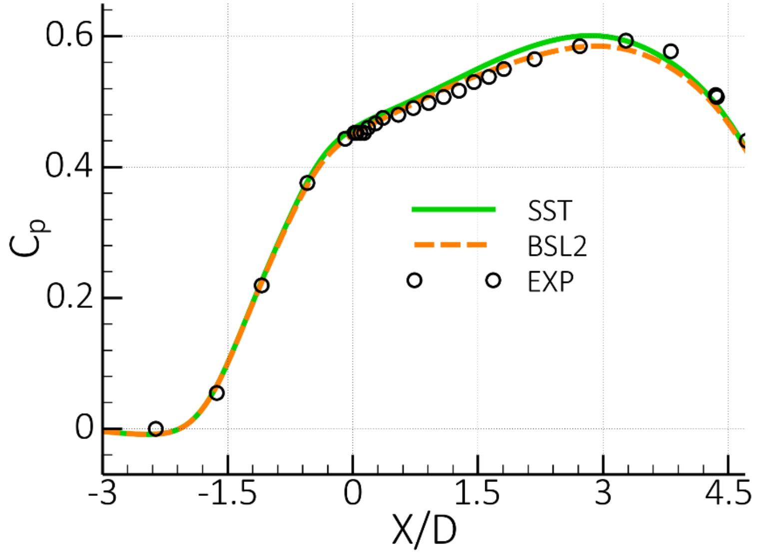
CS0 Axisymmetric Diffuser

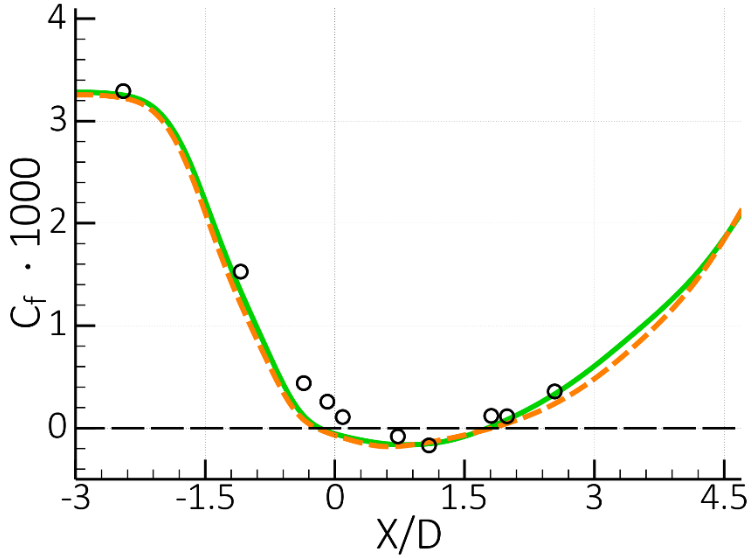
Flow scheme

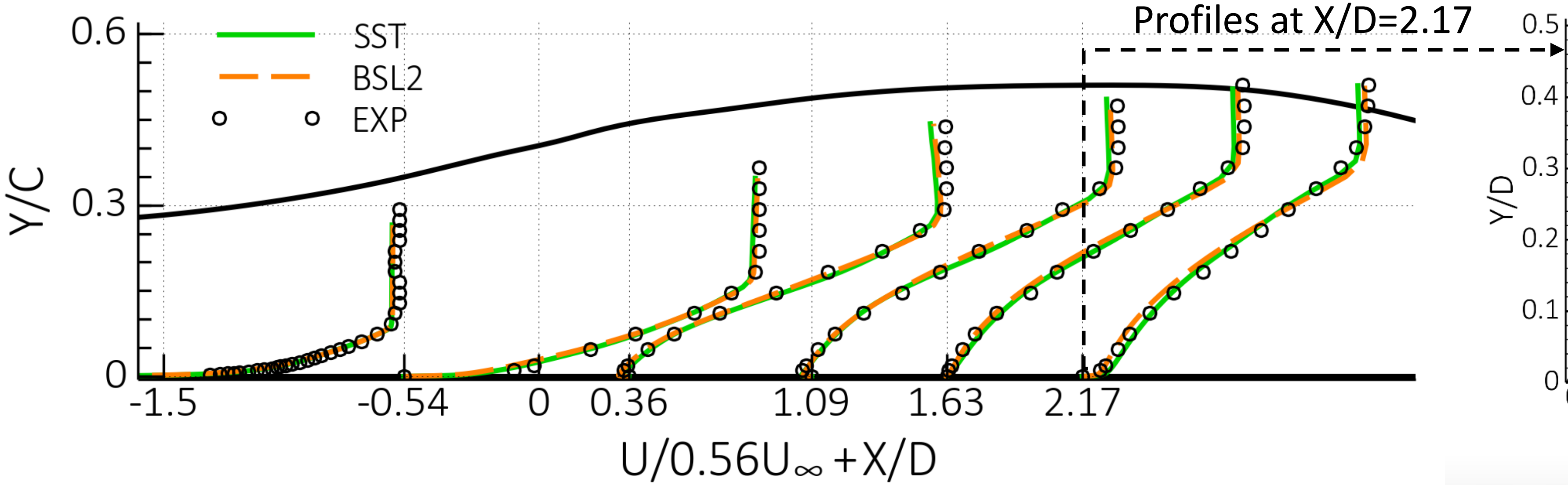


- Incompressible flow
- Re = $U_\infty \cdot D/\nu = 2.8 \cdot 10^5$
  - D = 0.14 [m] – Diffuser diameter
  - U_∞ = 30 [m/s] Freestream uniform velocity

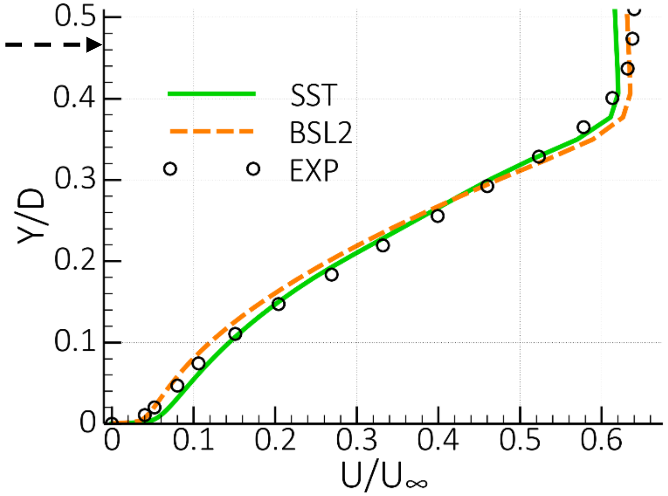
Pressure and skin friction coefficient on he bottom wall





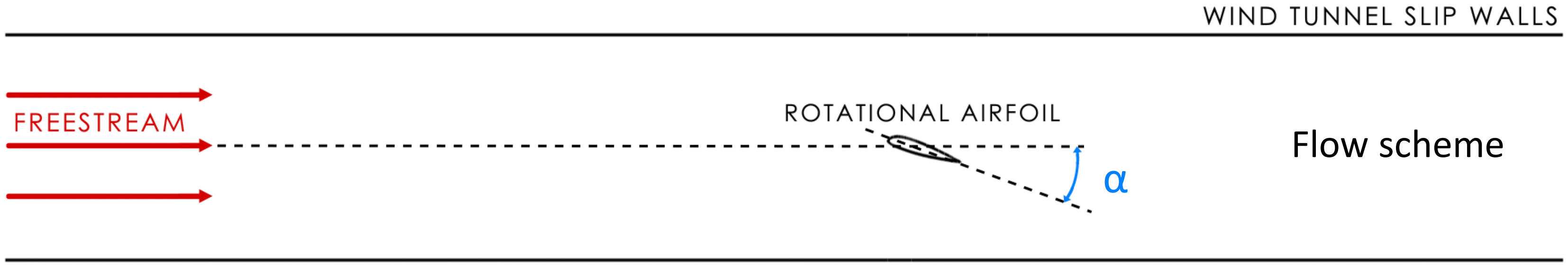


Profiles at X/D=2.17



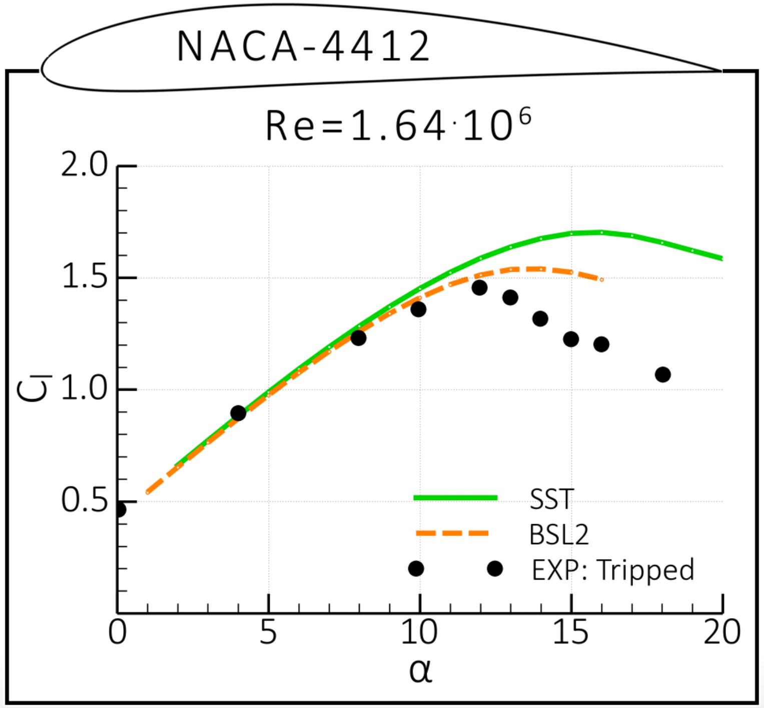
Flow Around Airfoils in Wind Tunnels

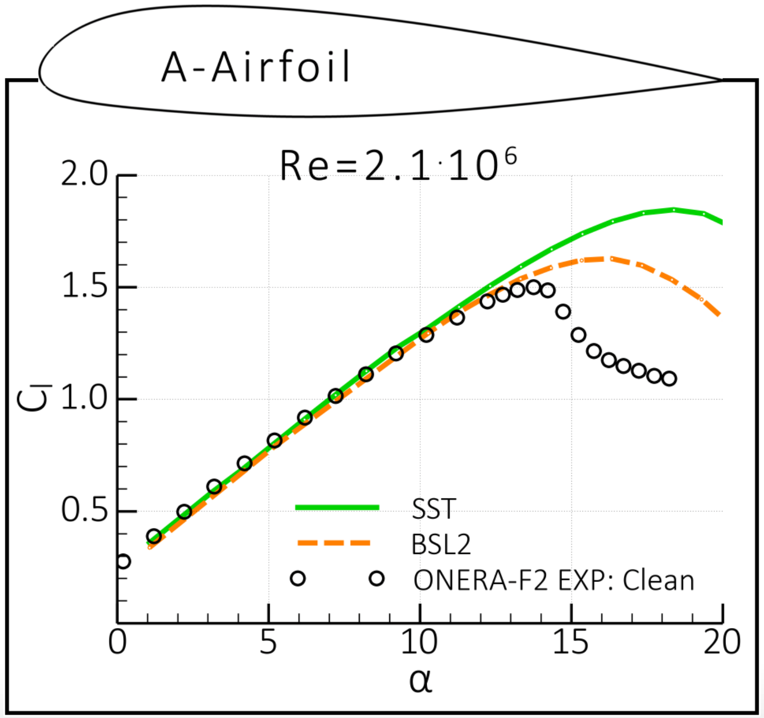
- Incompressible flow
  - $Re = U_\infty \cdot C/\nu$
  - $\alpha = 0^o\text{-}20^o$

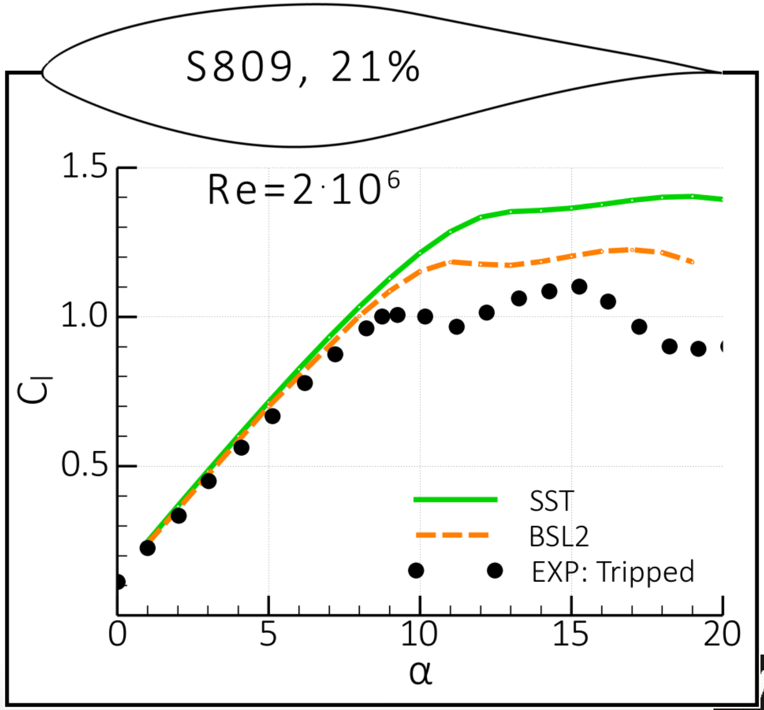


Flow scheme

- The size of computational domains corresponds wind tunnel parameters
- Uniform freestream corresponded experimental values is specified at the inlet

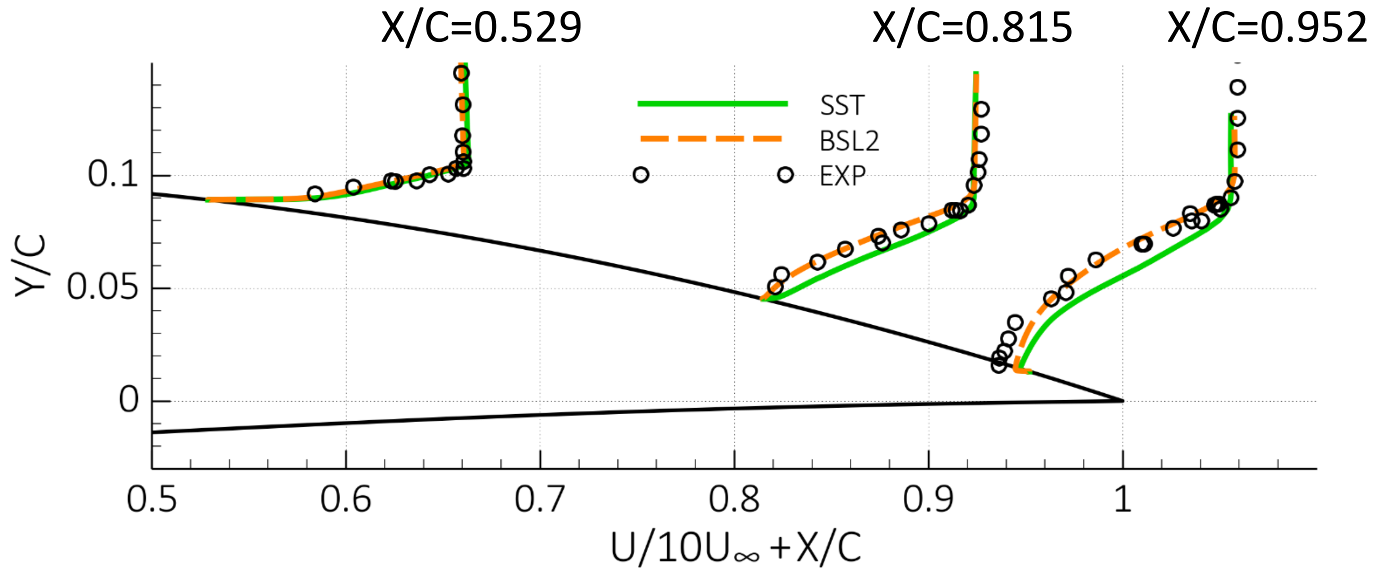




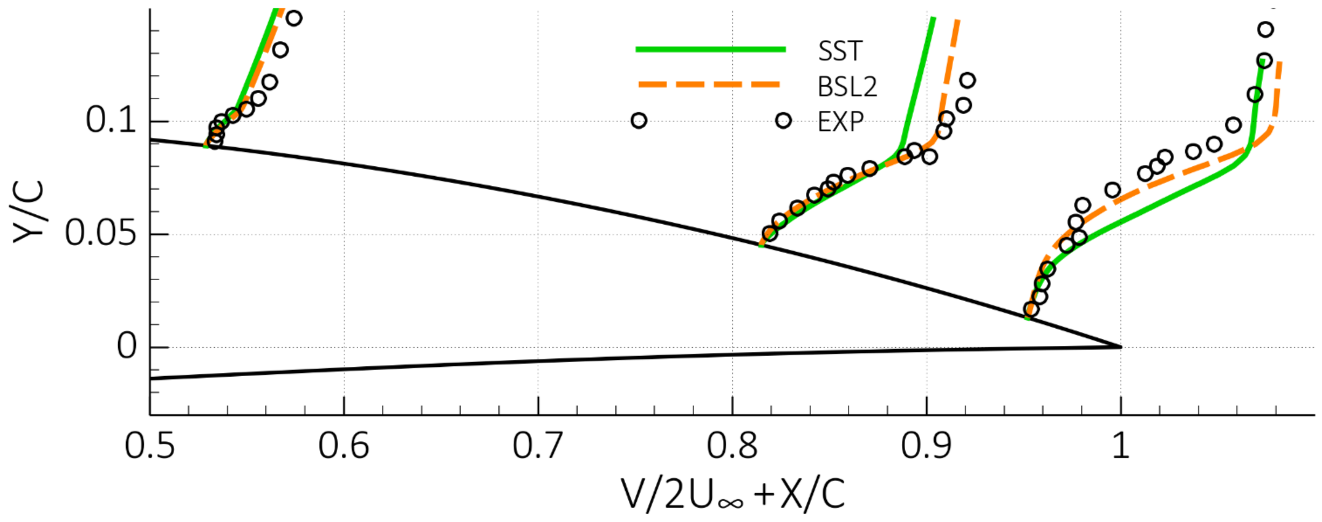


Flow Around Airfoils in Wind Tunnels: NACA-4412 at α=12°

Streamwise Velocity Profiles

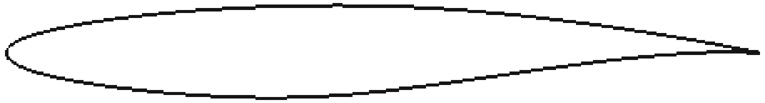


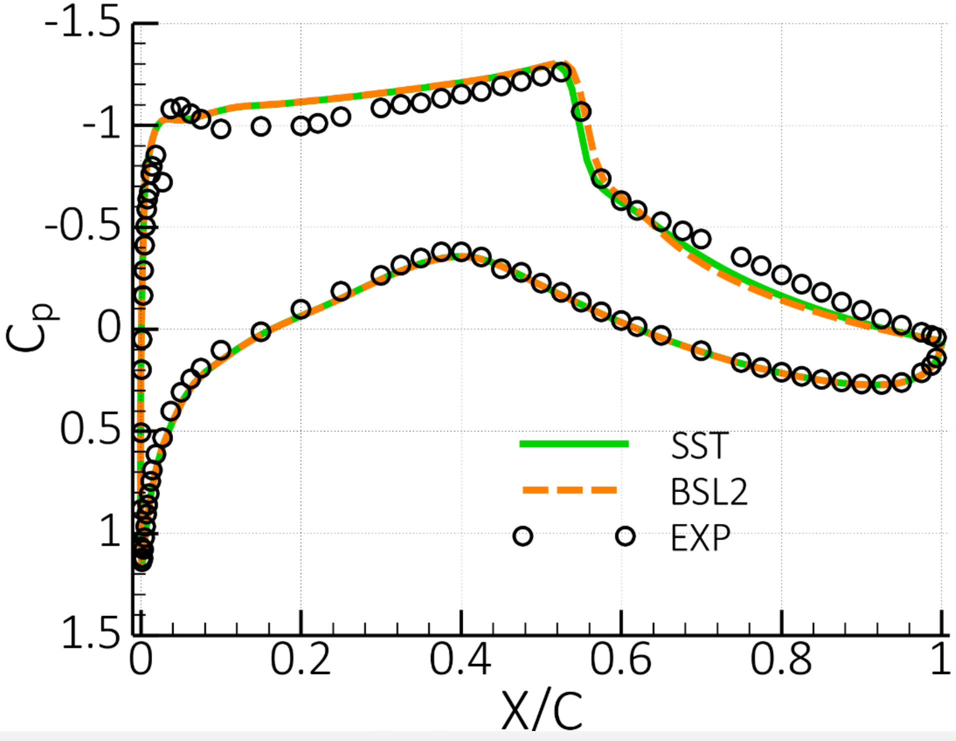
Wall Normal Velocity Profiles



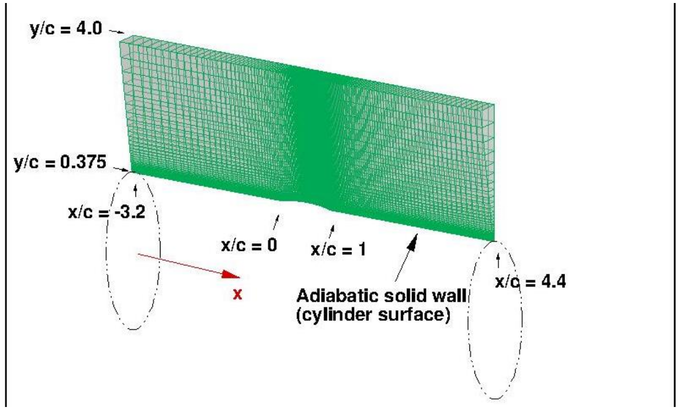
Transonic Flows

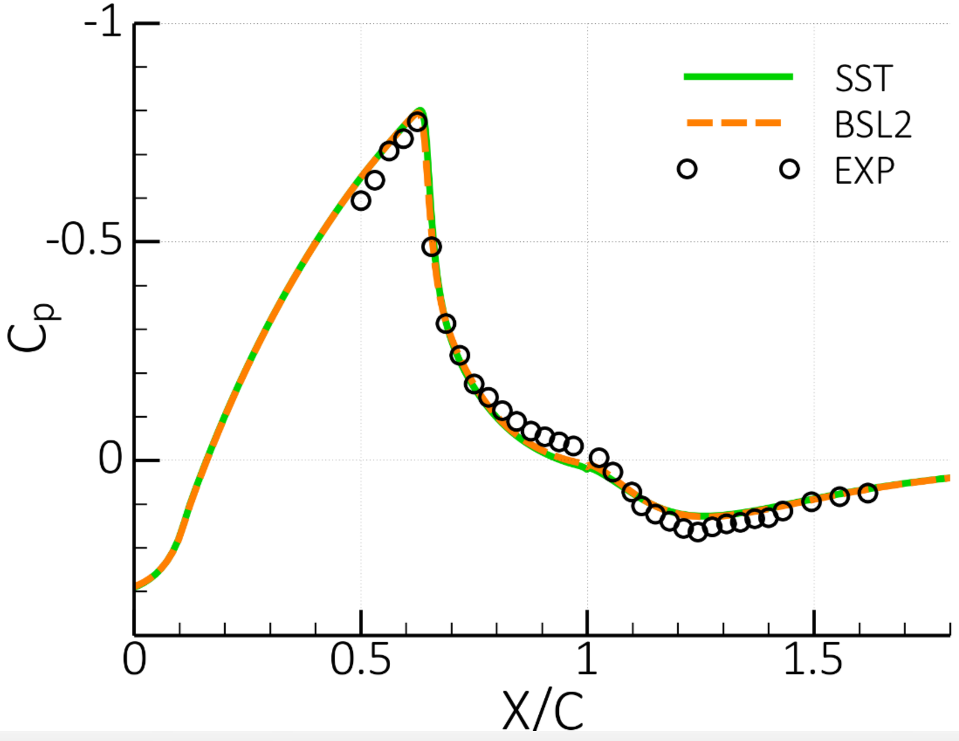
- RAE-2822, Case-10
  - Re = $6.2 \cdot 10^6$
  - Ma = 0.75
  - Pr = 0.7
  - $\alpha = 3.19^o$ – angle of attack





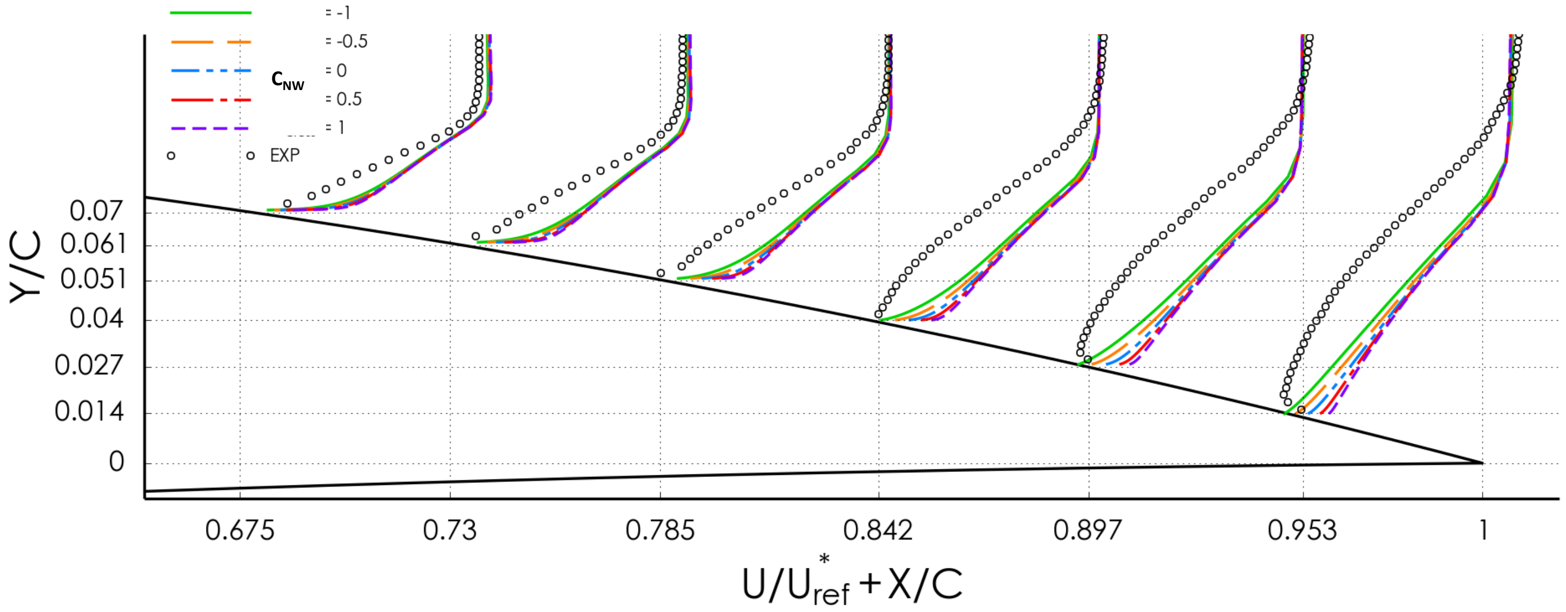
- Axisymmetric Transonic Bump
  - Re = $2.763 \cdot 10^6$
  - Ma = 0.875
  - Pr = 0.7

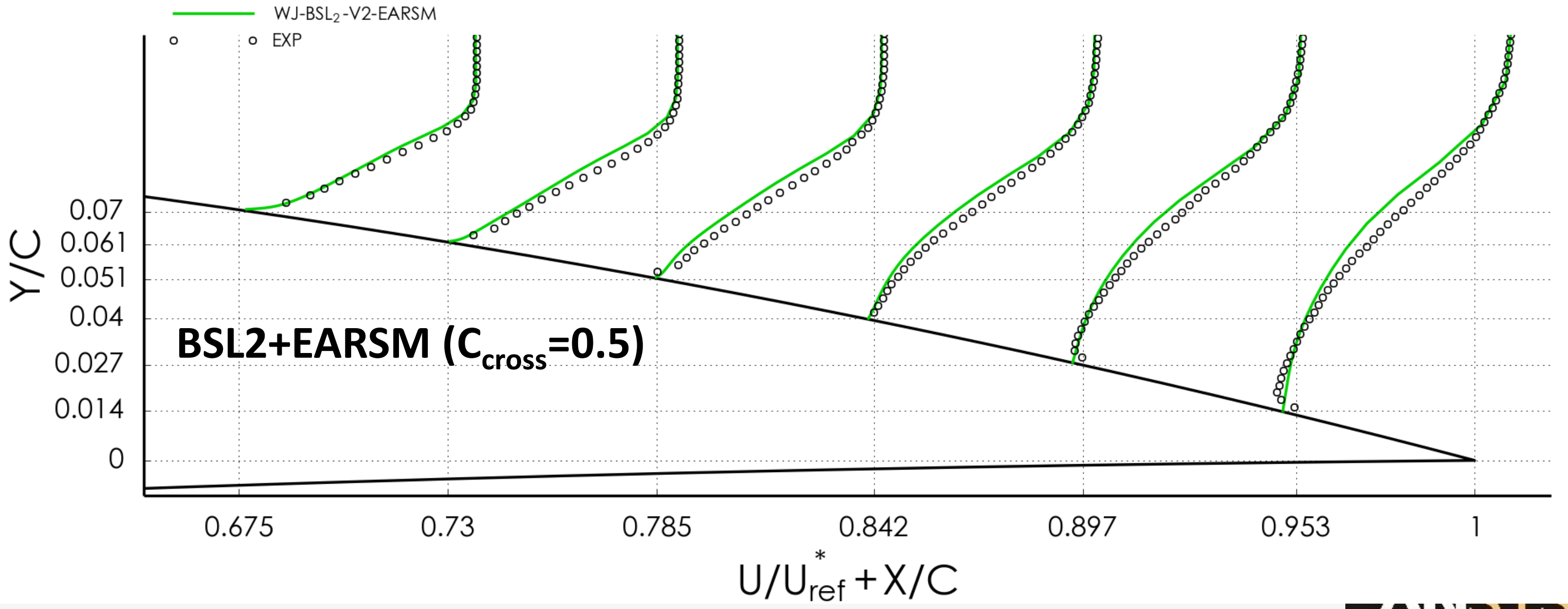




Flow around a NACA-4412 airfoil

- Combination of BSL2 (R18) with EARSM gives improved separation prediction without need to adjust C_{Sep}!
- For this reason alone, a proper two-equation model should be adjustable, so that it can be used stand-alone or in combination with RSM/EARSM





Summary - RANS

- SST Model not aggressive enough for prediction of Cl_{max} on airfoils
- SST-HL model tuned for that purpose – slight over-separation for transonic flows
- NACA 4412 – should probably abandon Coles-Wadcock (1979) experiment
- BSL2
  - Model with free coefficients
  - Can be tuned over a wide range of flows by the user
  - Coefficient settings (C_{SEP}=2, C_{MIX}=0.35, C_{NW}=0.5) can do all flows (CS0, backstep, all Airfoils, RAE 2822, B-J bump) – therefore more consistent than SST
  - Can BSL2 replace existing scale-equations?
  - Intermediate step to machine learning (ML)