NASA Ames Research Center, December 10, 2015
Advanced Modeling & Simulation Seminar Series (AMS)

Numerical Investigation of Flow Phenomena in a Planar Expansion-Defletion Nozzle

Gerrit-Daniel Stich[1,2,3]
Bernd Wagner[1], Stefan Schlechtriem[1,2]

(1) DLR – German Aerospace Center, Institute of Space Propulsion
(2) University of Stuttgart, Institute for Space Systems
(3) Stanford University, Unsteady Flow Physics and Aeroacoustics Lab



DLR

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Stich, G., Wagner, B. & Schlechtriem, S. (2015). Numerical Investigation of Flow Phenomena in a Planar Expansion-Deflection Nozzle. *In European Symposium on Aerothermodynamics for Space Vehicles.*

Stich, G., Wagner, B. & Schlechtriem, S. (2015). Computational Investigation of Flow Prediction for Separated Nozzle Flows using DLR TAU Code. *In Deutscher Luft- und Raumfahrtkongress 2015.*



DLR

1. Introduction
2. Numerical Method and Flow Solver
3. Validation
4. The Expansion-Deflection Nozzle (ED)
5. Variation of Nozzle Pressure Ratio (NPR)
6. Conclusion

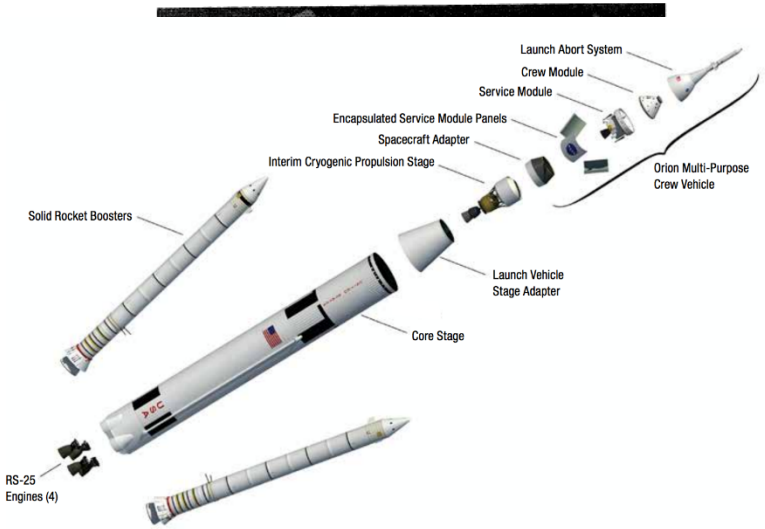


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1. Introduction

1.1 Why using a Expansion-Deflection (ED) nozzle? A historical review!



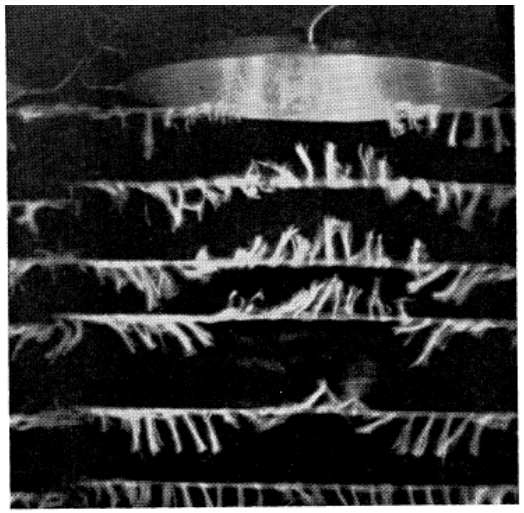


Fig. 5b Schlieren and tuft photograph of flow in an E-D nozzle at low pressure ratio

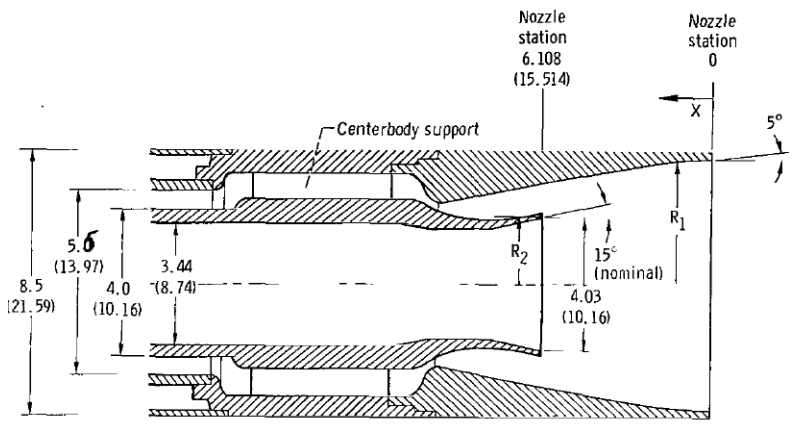
growing need for higher payloads m_P

⇩ possibility to increase performance

1960s Rao: ED-Nozzle as a altitude compensating propulsion system

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(d) Expansion-deflection nozzle.

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⇩ altitude compensation in doubt, complex flowfield

1960s/70s Wasko: altitude compensation in doubt

⇩ improved numerical methods

2002 Taylor & Hempsell: intensive numerical study of nozzle geometrie and performance

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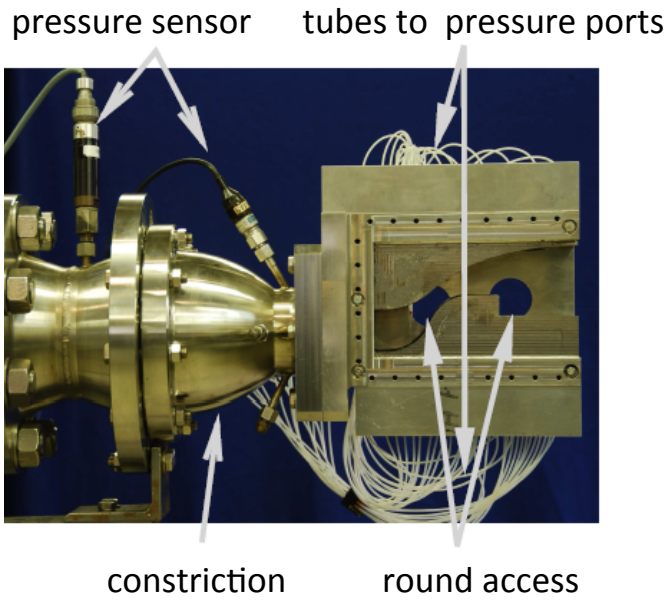
↓ lower structural mass due to shorter nozzle length

2005 Goetz: advanced upper stage propulsion concept for ARIANE 5 ESC-B

http://images.vice.com/motherboard/content-images/contentimage/12220/1400079898889493.png



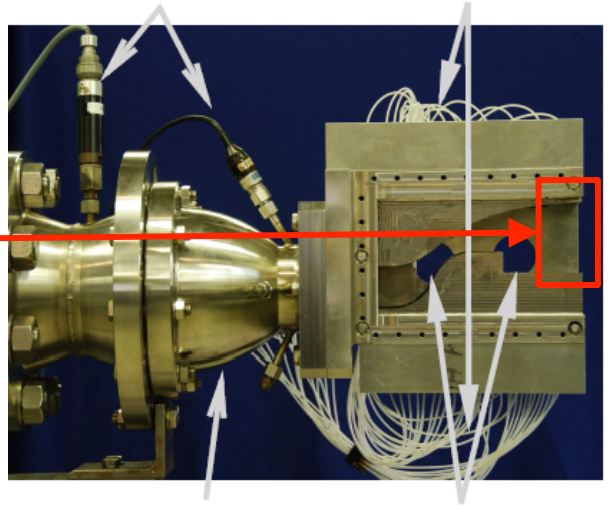
Wagner: intensive numerical and experimental study of the flow field in a planar Expansion-Deflection Nozzle (ED)



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Side-wall separation for selected Nozzle Pressure Ratios (NPR)





1. Introduction

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Wagner: intensive numerical and experimental study of the flow field in a planar Expansion-Deflection Nozzle (ED)

⇩

Side-wall separation for selected Nozzle Pressure Ratios (NPR)

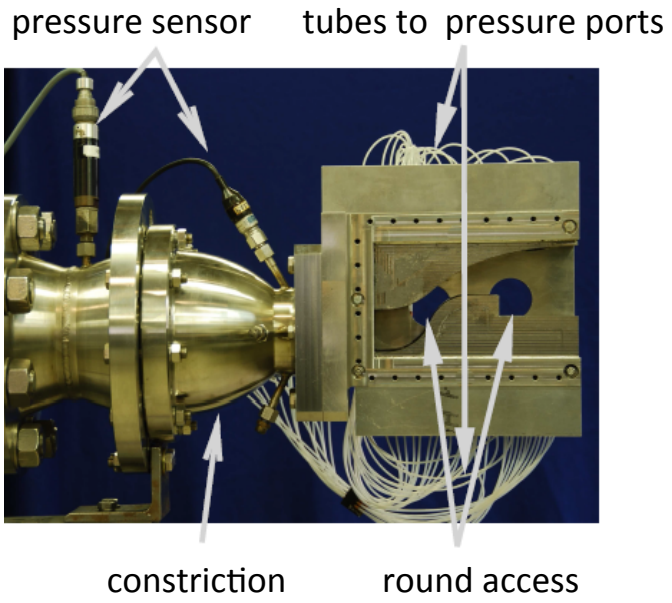
⇩ **main goal of thesis**

- **How do the side-walls effect the simulation?**
- **Can the numerics capture the side-wall separation?**

⇩ **Spin-off**

Transition between two operation modes

Simulation of Backward Facing Step (BFS) & Truncated Ideal Contour Nozzle (TIC)



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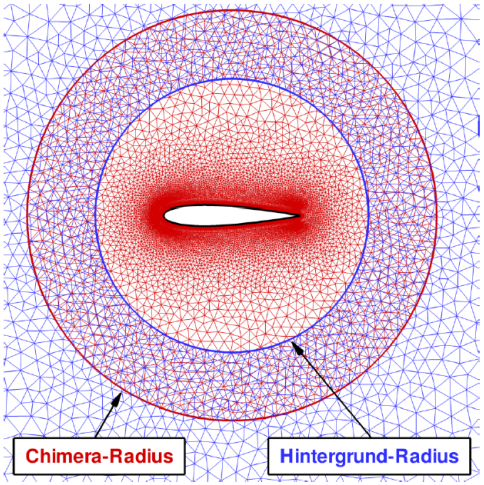


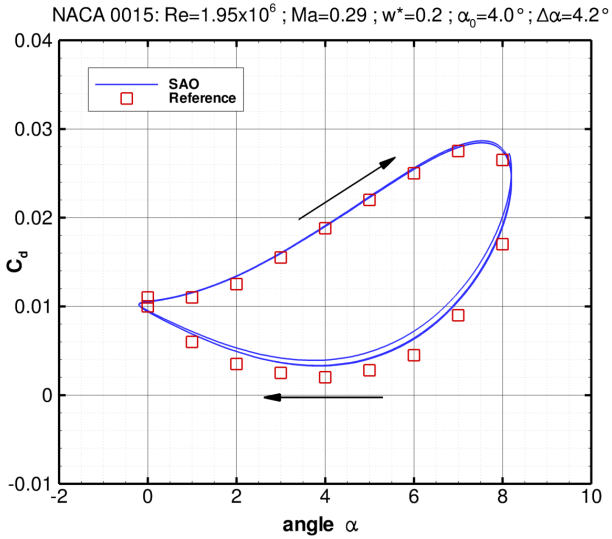
2. Numerical Method and Flow Solver

2.1 What is the DLR-TAU Code…..

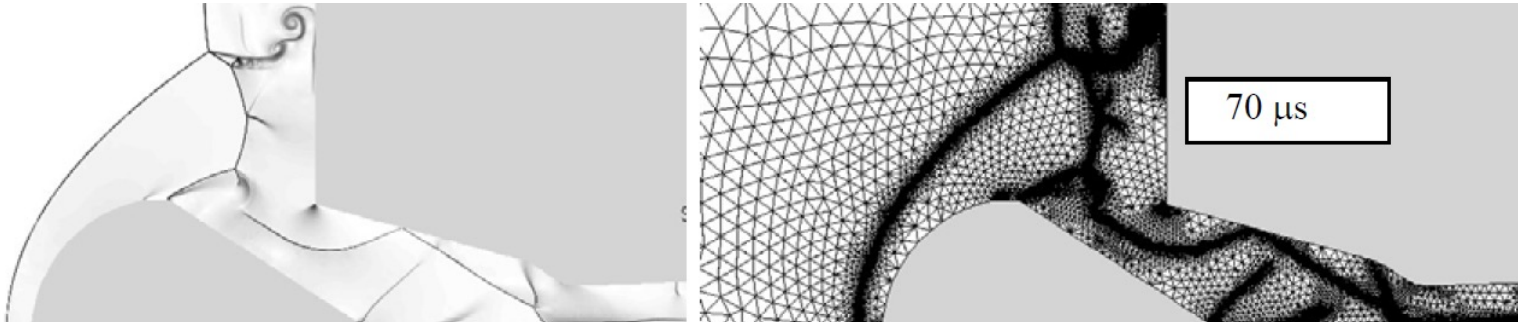
*"... actually not one code but a modern software system for the prediction of **viscous** and **inviscid** flows about complex geometries from the low **subsonic** to the **hypersonic** flow regime, employing hybrid unstructured grids!"*

- Grid partitioning
- Pre-processing
- Solver (RANS, RSM, DES, LES)
- Adaptation
- Deformation
- CHIMERA technique





Chimera technique used for flow over oscillating airfoil (Gerrit Stich, 2013)



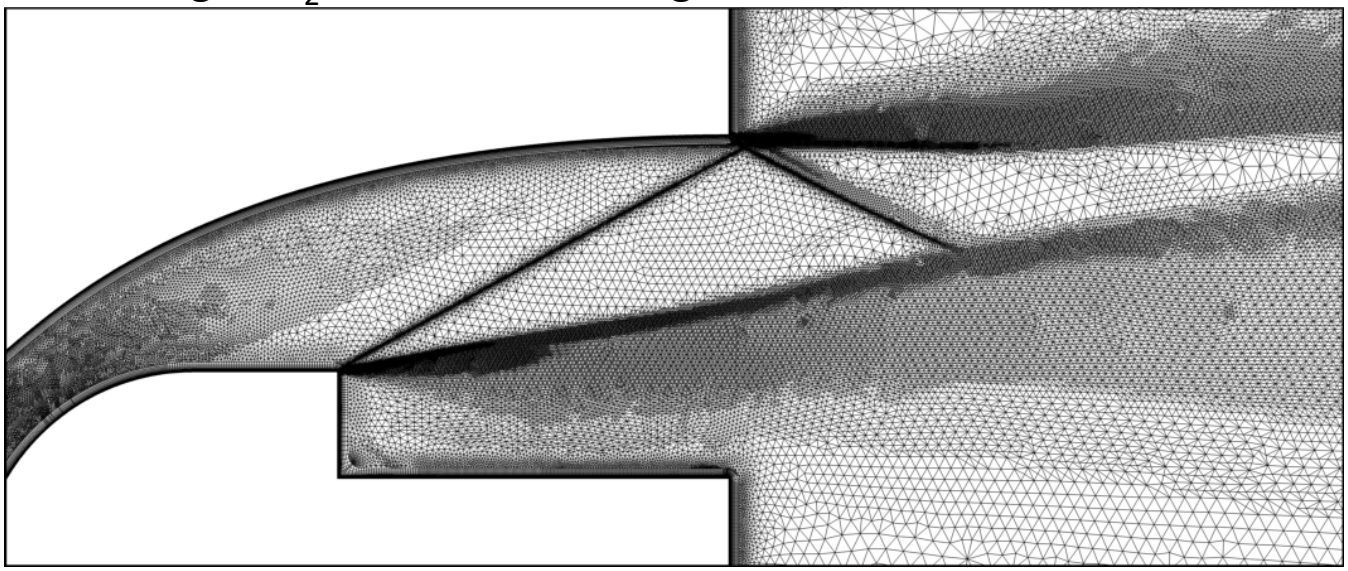
The DLR-TAU Code: Recent Applications in Research and Industry (Schwamborn et.al, 2006)



2. Numerical Method and Flow Solver

2.1 Numerical settings of the DLR-TAU Code in this study

- AUSMDV Upwind with second order MUSCL
- Relexation solver: Implicit Backward Euler
- Linear Solver: LU-SGS
- Residual smoother: Upwind implicit
- Turbulence model: SAO, Menter SST, kw-Wilcox, RSM
- Intensive use of mesh adaptation
- Control of computations via python script
- Ideal gas with nitrogen N_2 as a medium using Sutherland's law

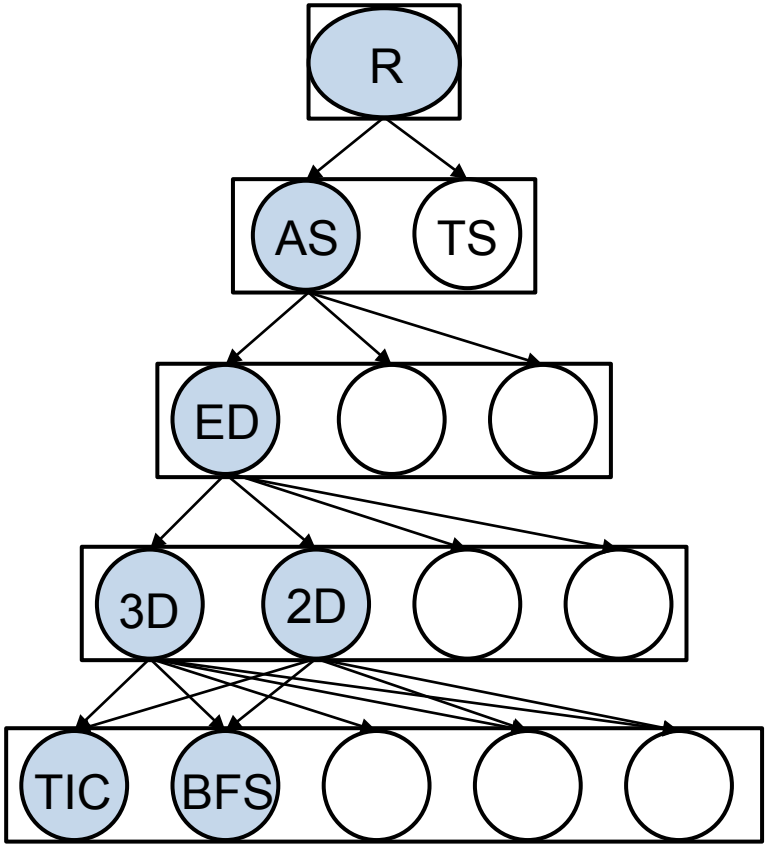


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3. Validation

3.1 Principle of validation and verification according to AIAA guide



Complete system

System cases

Subsystem cases

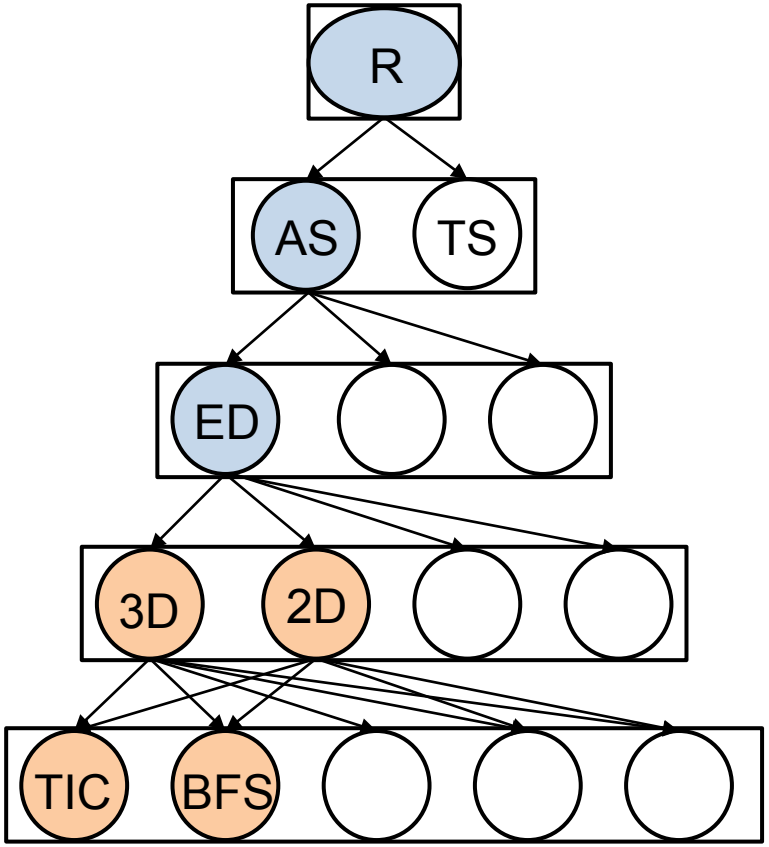
Benchmark cases

Unit problems

Adapted from:
AIAA Guide for the verification and validation of computational fluid dynamic simulations. AIAA-G-077-1998, 1998

3. Validation

3.1 Principle of validation and verification according to AIAA guide



Complete system

System cases

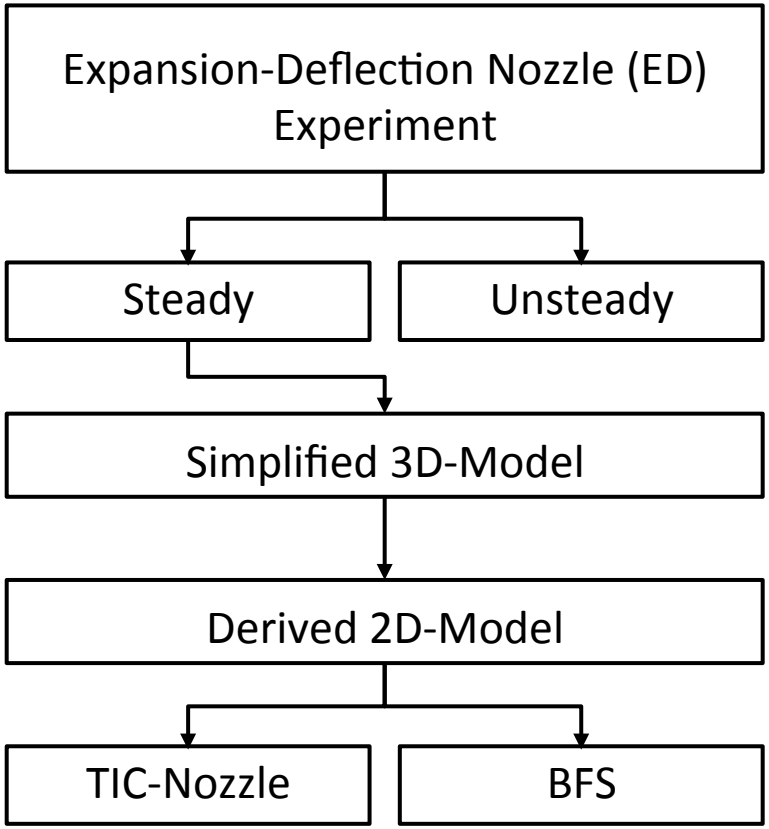
Subsystem cases

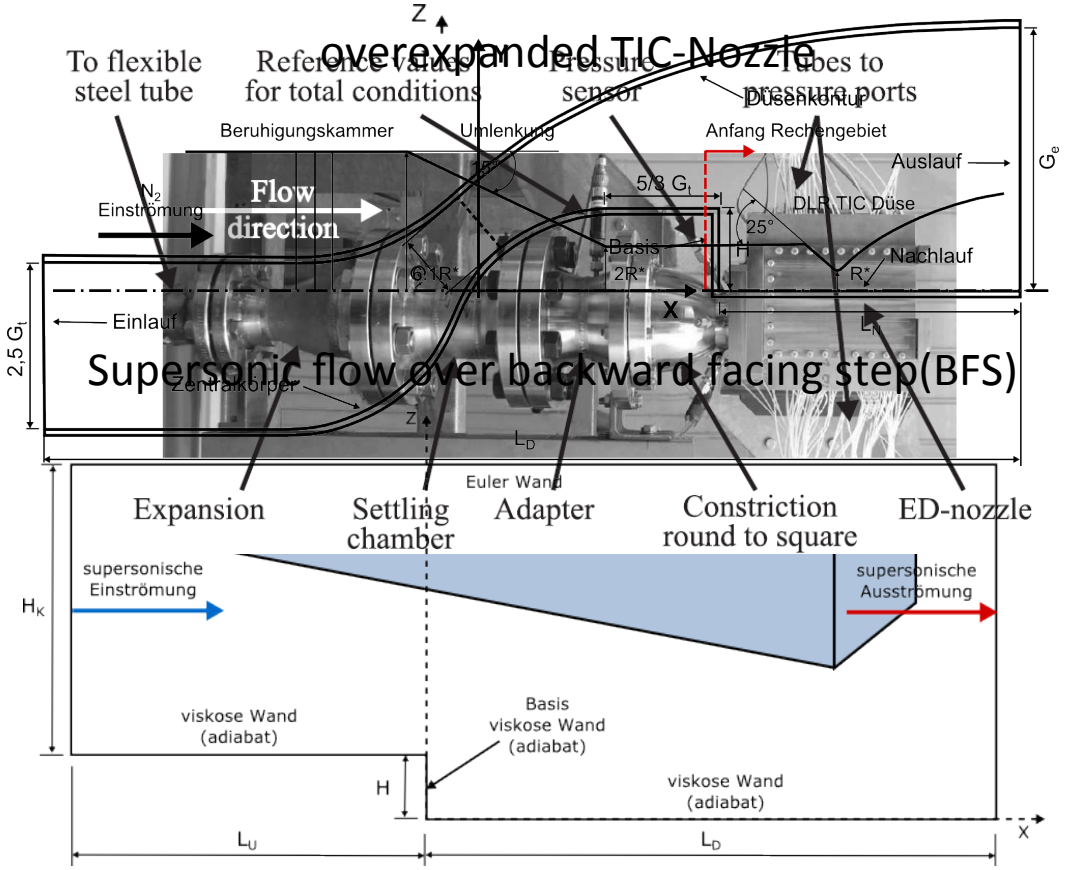
Benchmark cases

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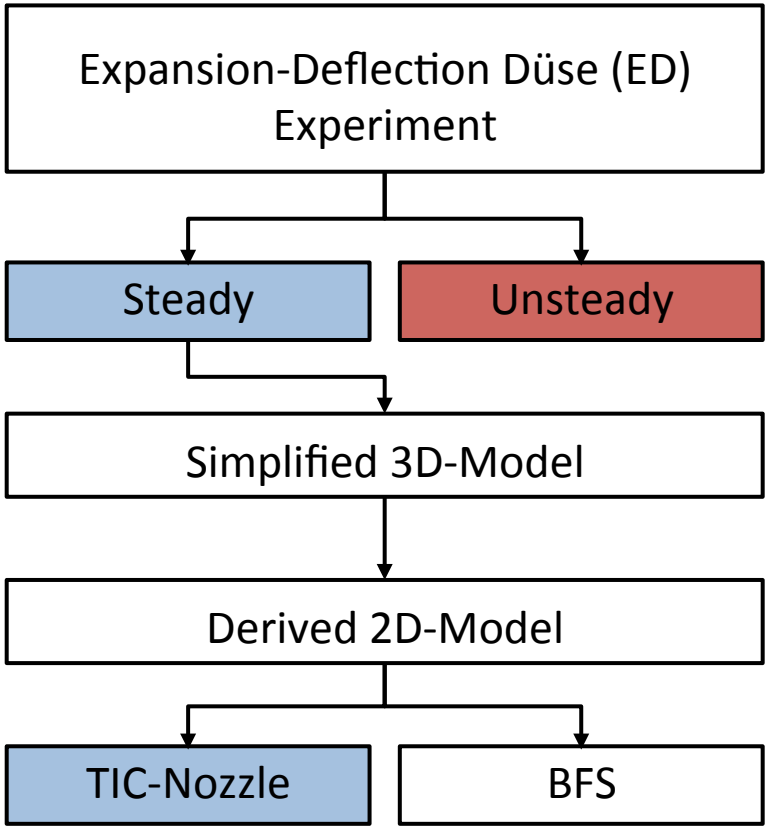
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AIAA Guide for Verification and Validation:

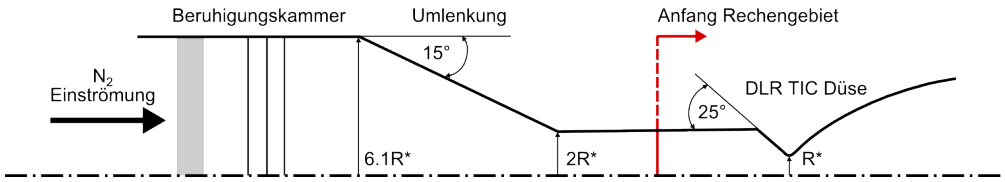




AIAA Guide for Verification and Validation:



overexpanded TIC-Nozzle



Test Case 1A

-

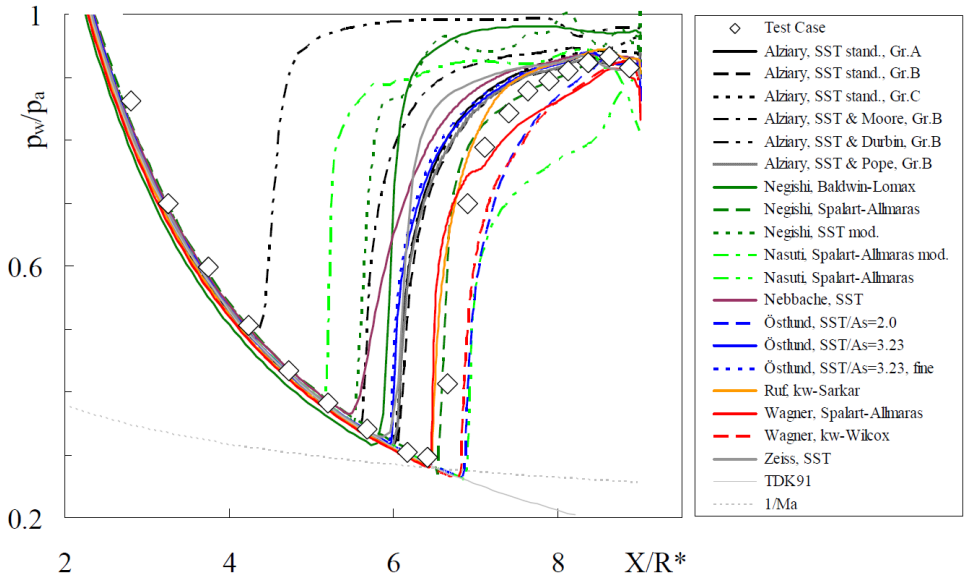
CFD-Workshop FSCD/ATAC Group 2006

Flow Conditions:

NPR = 25,0 ; T_0 = 283 K ; T_∞ = 300 K ; R* = 10,0 mm

3. Validation

3.3 Test Case 1A



Overexpanded TIC-Nozzle with separation

-

Test Case 1A

CFD-Workshop FSCD/ATAC Group 2006

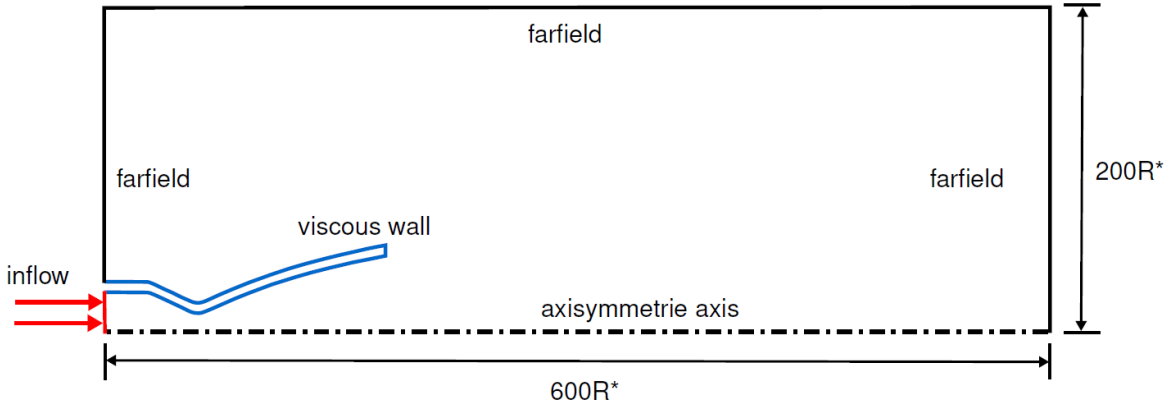
<u>Flow Conditions:</u>

NPR = 25.0 ; P0 = 25.0 [bar] ; T0 = 300 [K]

Current status of numerical flow prediction for separated nozzle flows

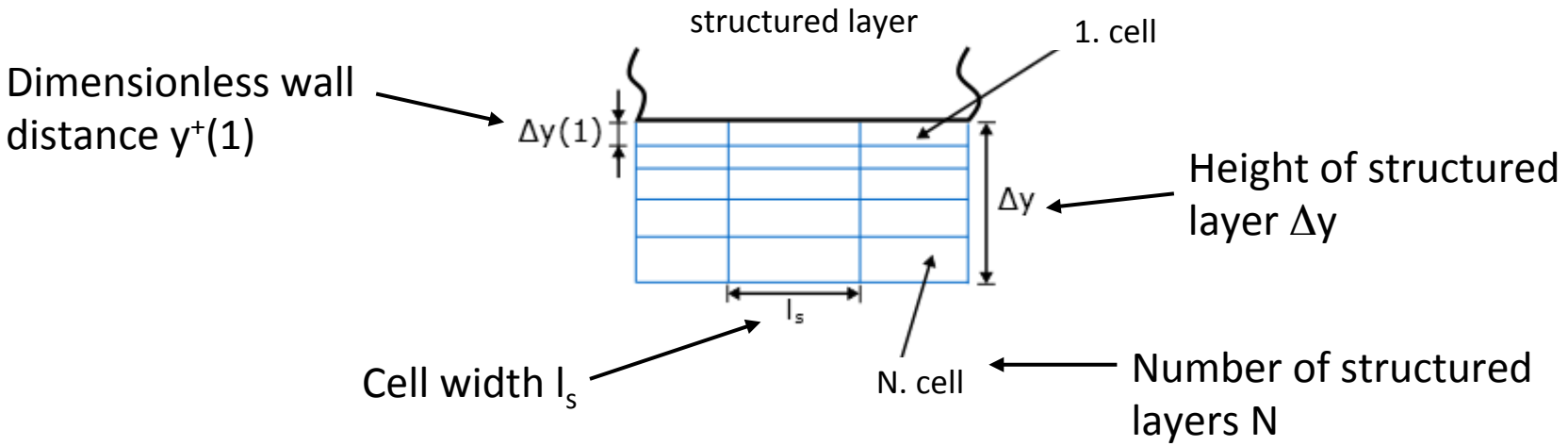
R. Stark and G. Hagemann

EUCASS 2007



Computational Domain

Observed Grid Parameter

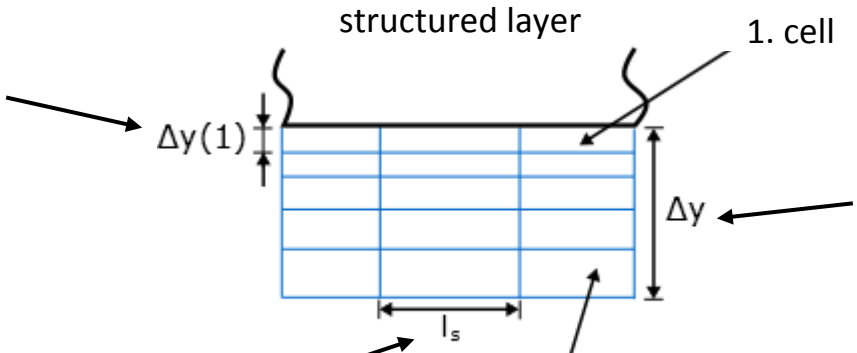


Additional Parameters:

- Influence of farfield distance in y and z direction
- Number of used adaptation steps
- Number of unstructured grid cells
- Influence of turbulence model
- Influence of flow parameters (NPR, T_0)
- Influence of nozzle length (truncation)

Observed Grid Parameter

Dimensionless wall distance $y^+(1)$



Height of structured layer Δy

Cell width l_s

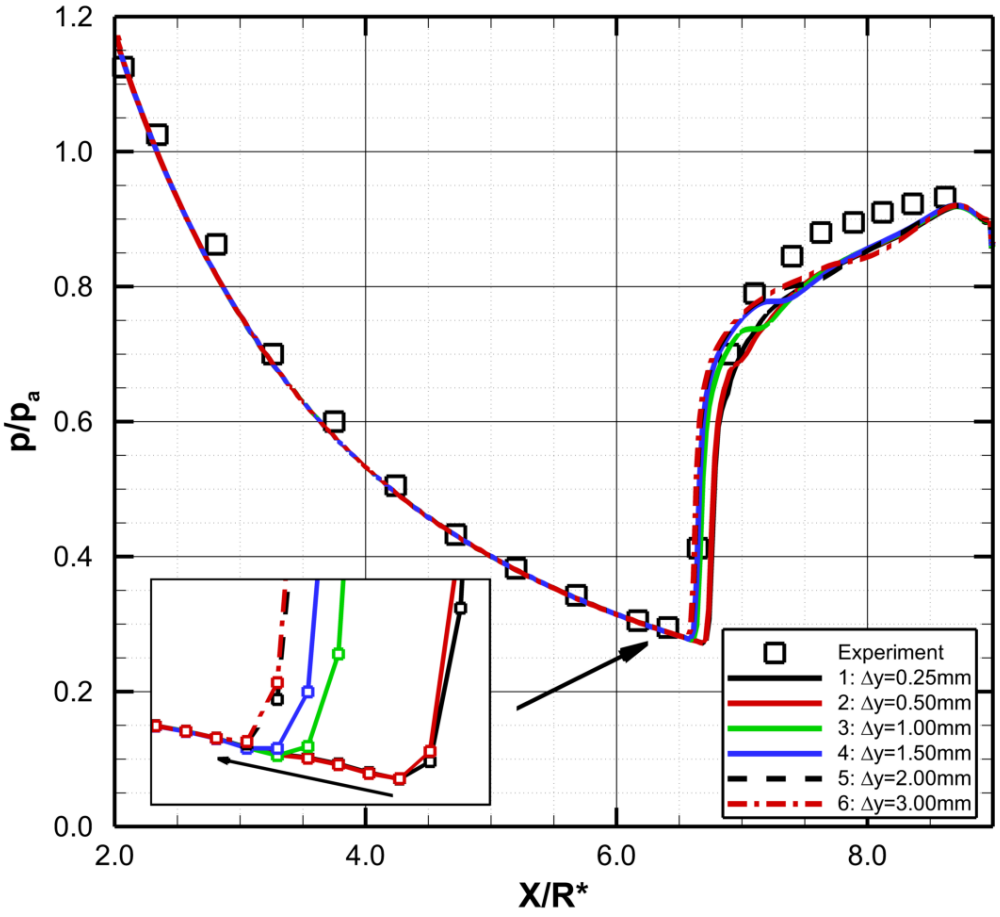
Number of structured layers N

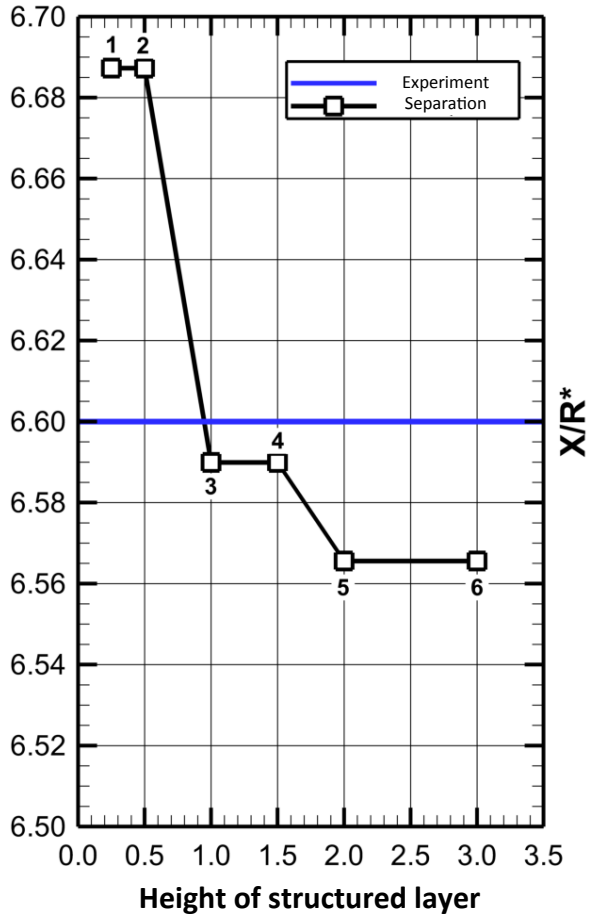
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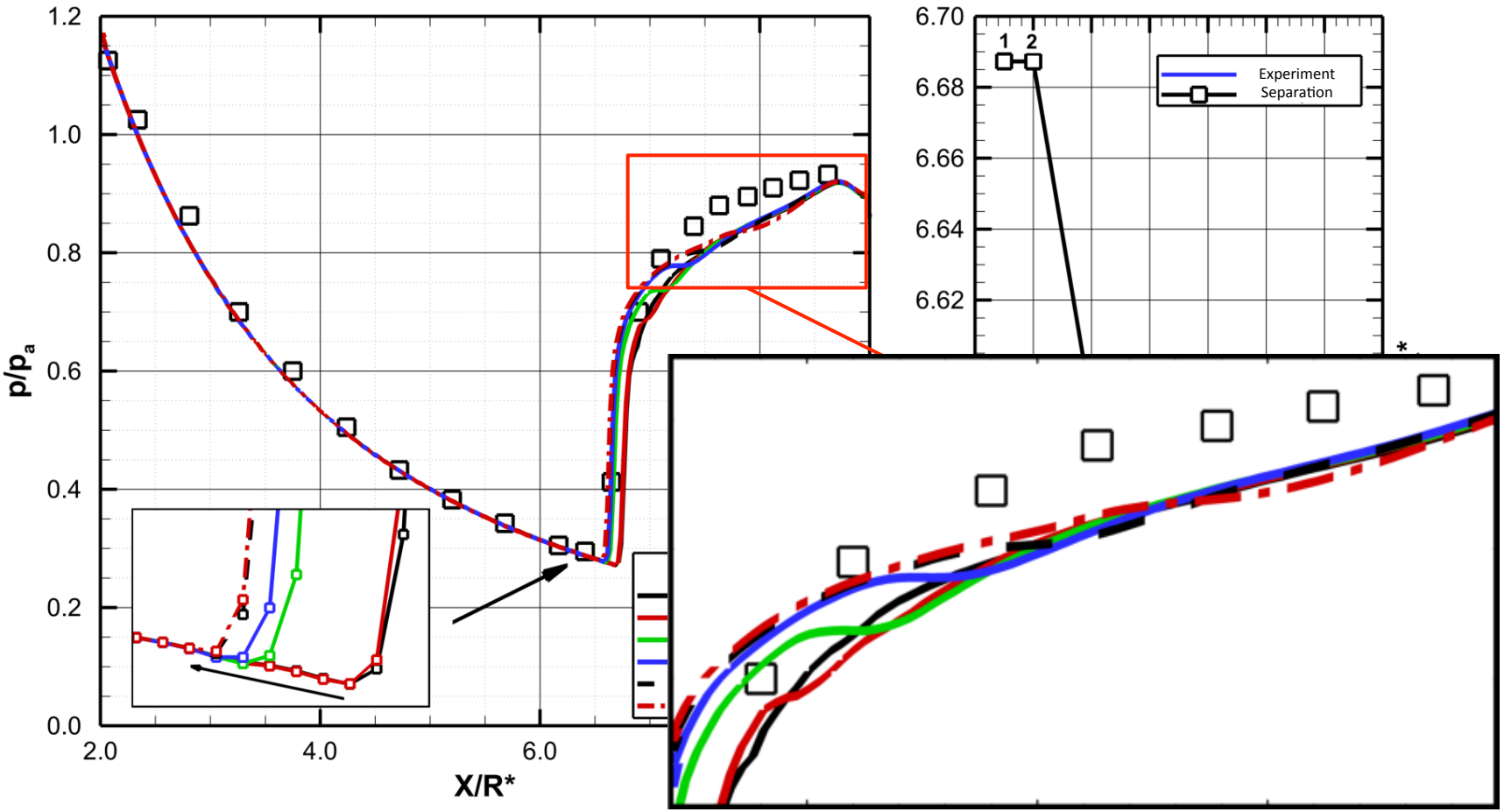


- Increase of stretching factor in 6 steps to obtain Δy_{min} = 0,25mm to Δy_{max}= 3,00mm

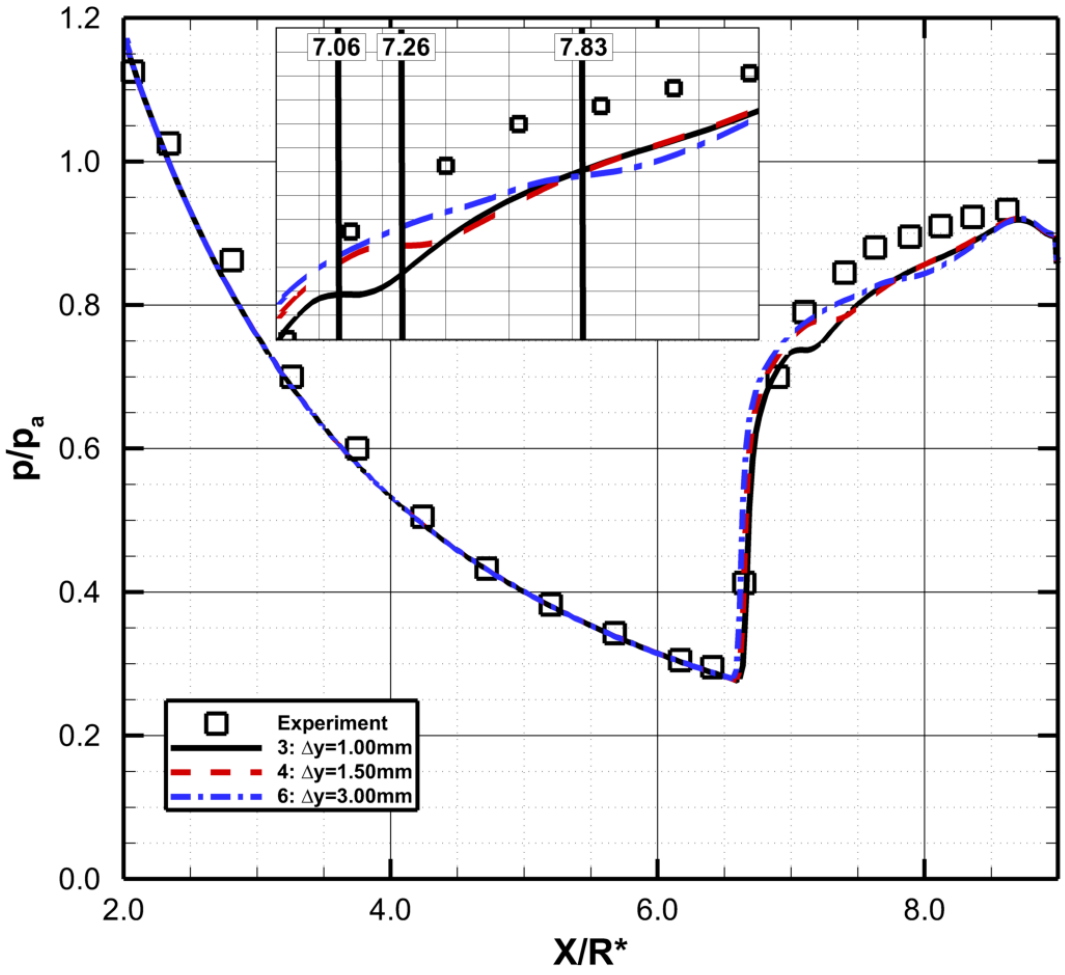


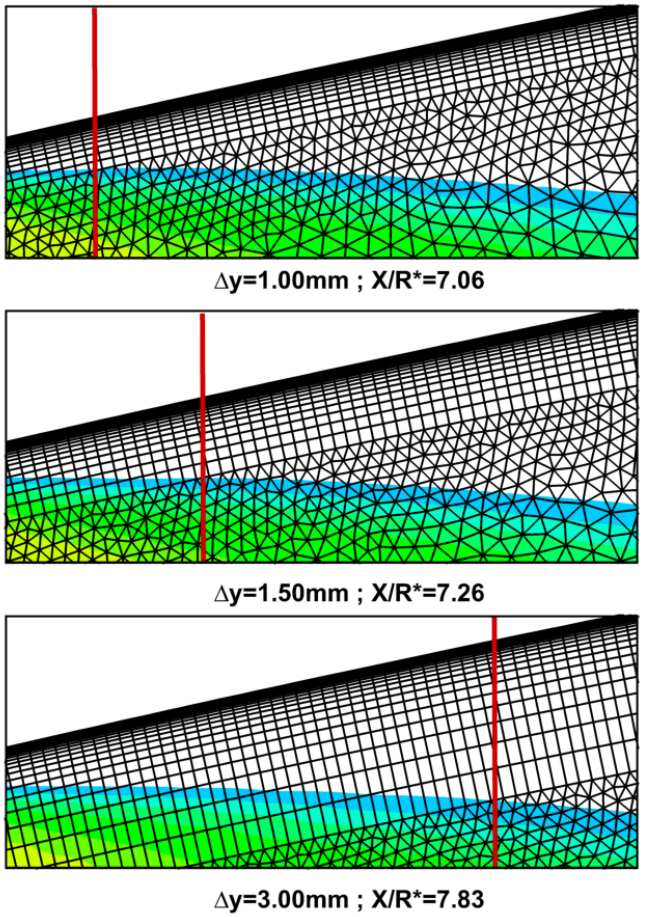


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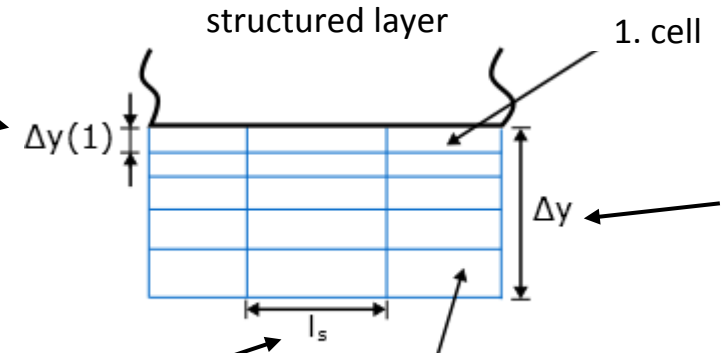
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Observed Grid Parameter

Dimensionless wall distance $y^+(1)$



Height of structured layer Δy

Cell width l_s

N. cell

Number of structured layers N

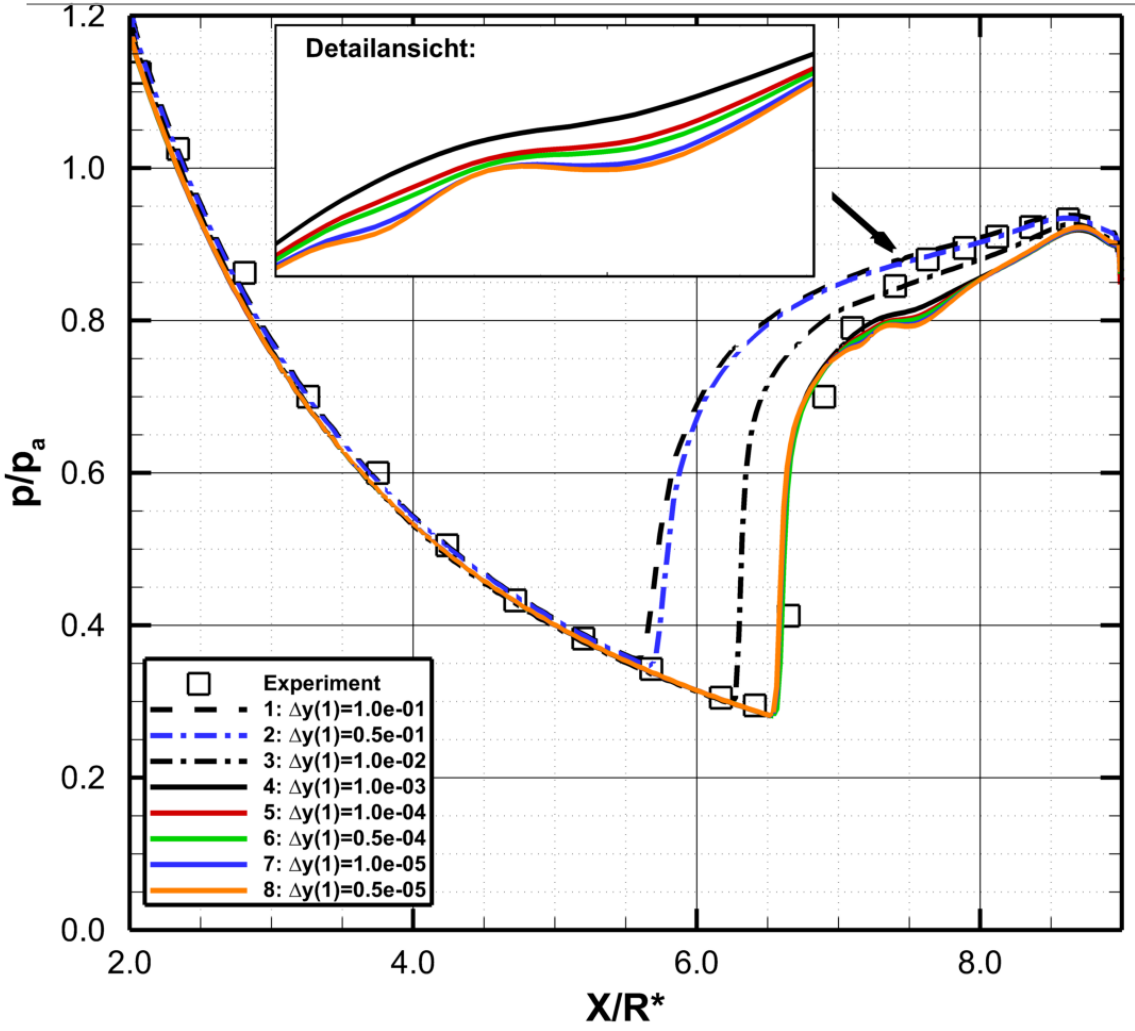
Additional Parameters:

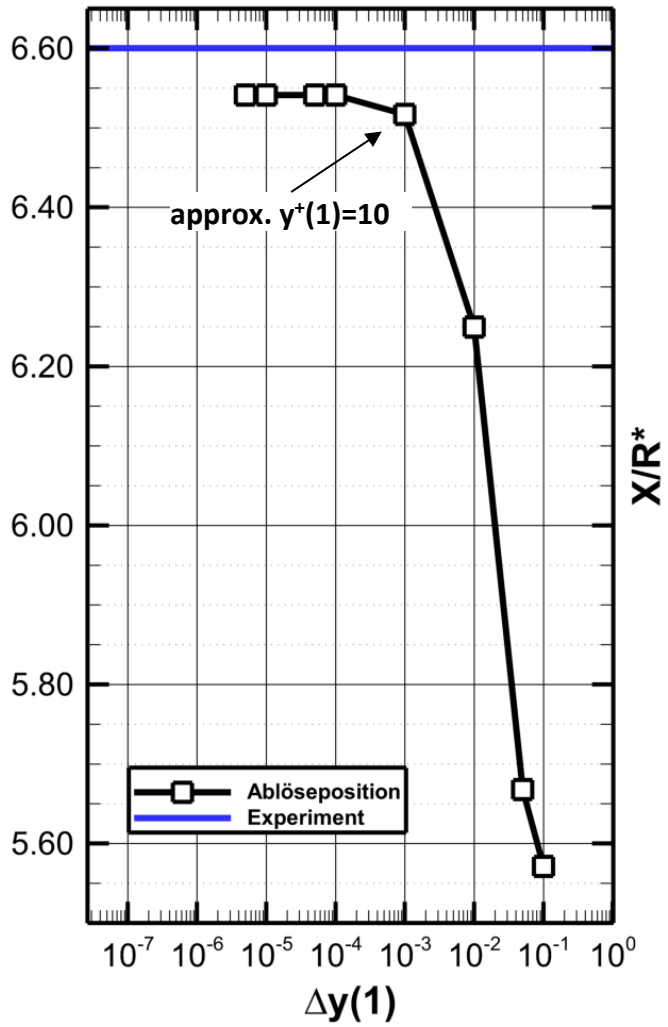
- Influence of Farfield distance in y and z direction
- Number of used adaptation steps
- Number of unstructured grid cells
- Influence of turbulence model
- Influence of flow parameters (NPR, T_0)
- Influence of nozzle length



3. Validation

3.3 Test Case 1A – dimensionless wall distance $y^+(1)$

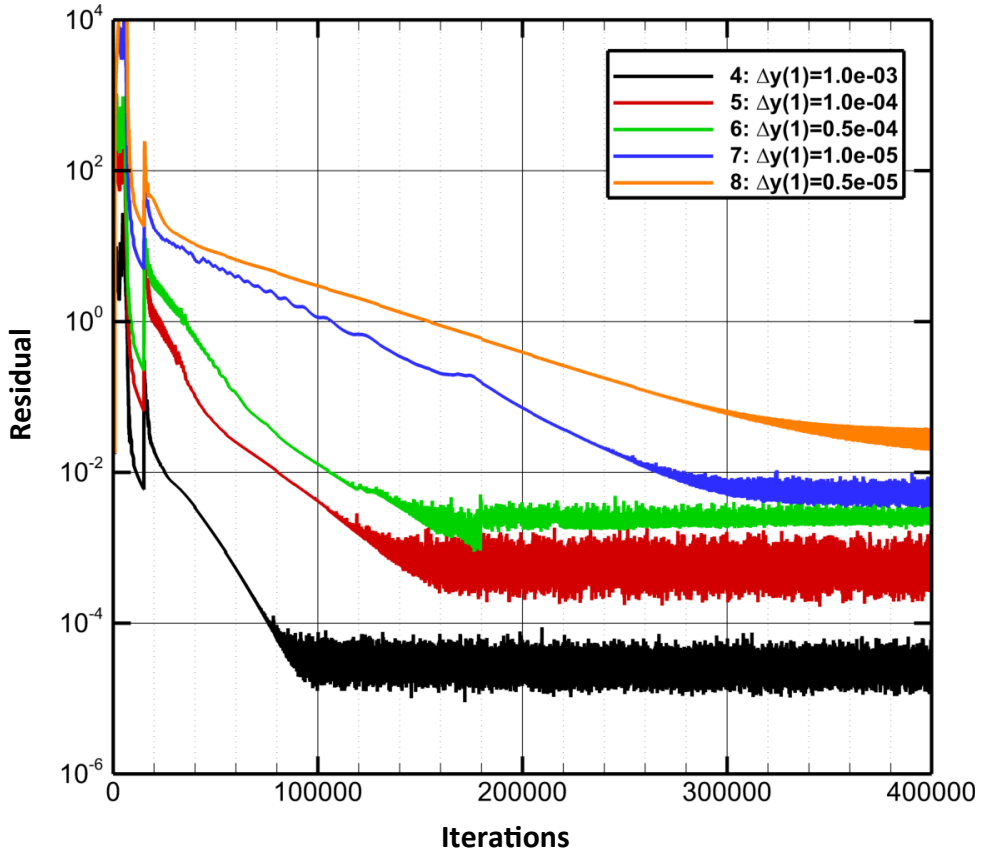


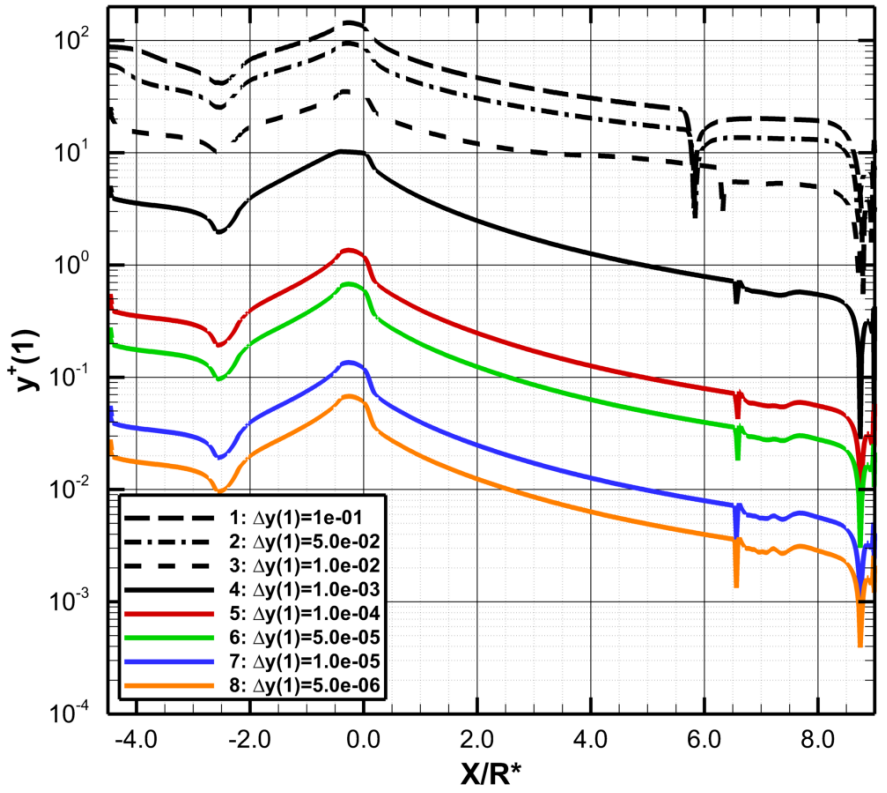


- For a dimensionless wall distance smaller than 10 the separation position converges towards a constant value

3. Validation

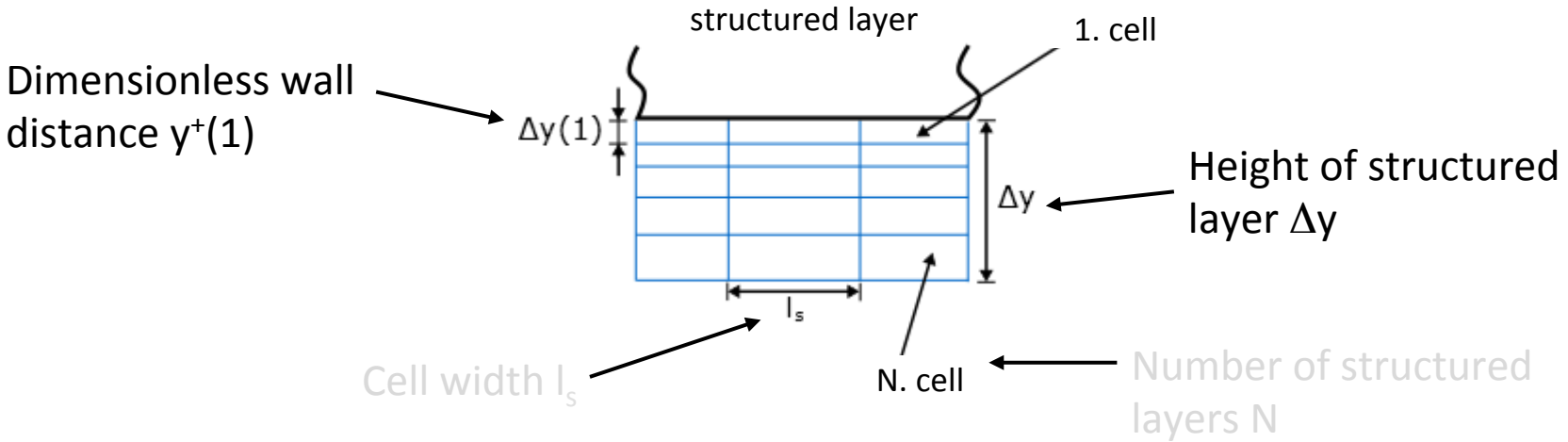
3.3 Test Case 1A – dimensionless wall distance y(1)





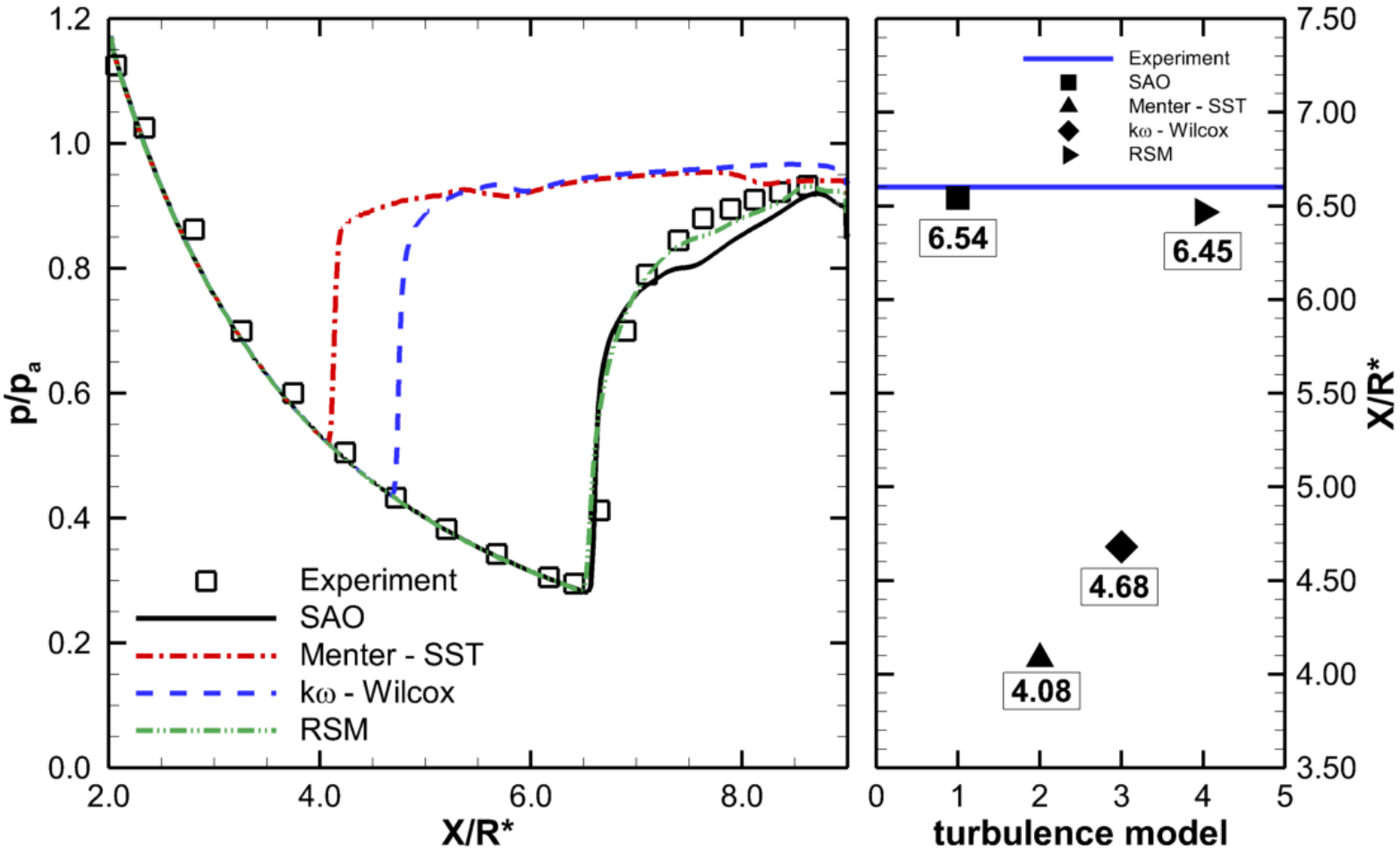
- To reduce the $y^+(1)$ value from 10 to 0.1 almost four times as many iteration steps are necessary

Observed Grid Parameter

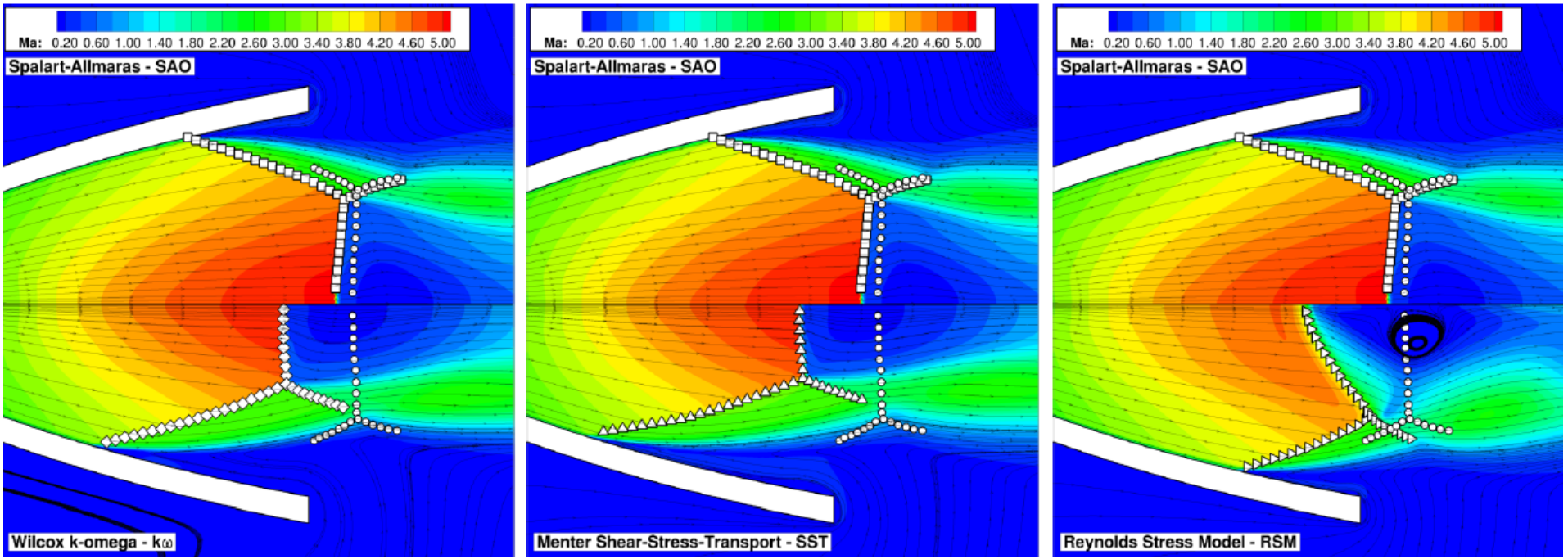


Additional Parameters:

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- Number of used adaptation steps
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- **Influence of turbulence model**
- Influence of flow parameters (NPR, T_0)
- Influence of nozzle length

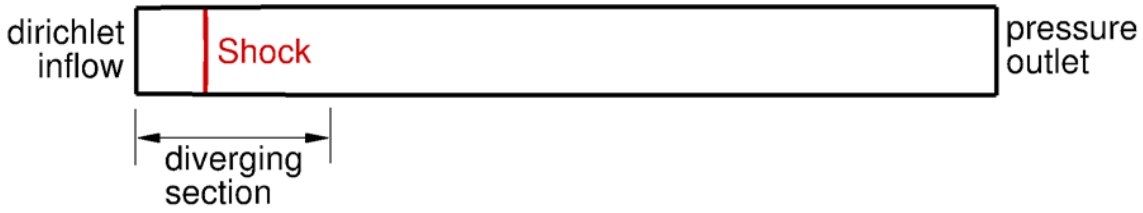


- Best agreement of wall pressure with SAO and RSM
- RSM predicts wall pressure in area of recirculation better

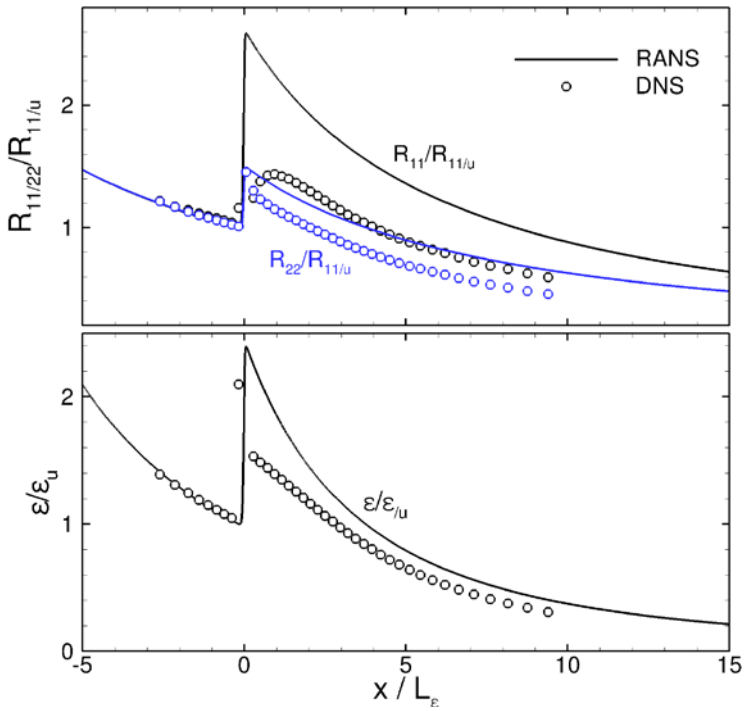


- Flow field for RSM model strongly differes close to mach disc
- Turbulence production across the shock is predicted too high

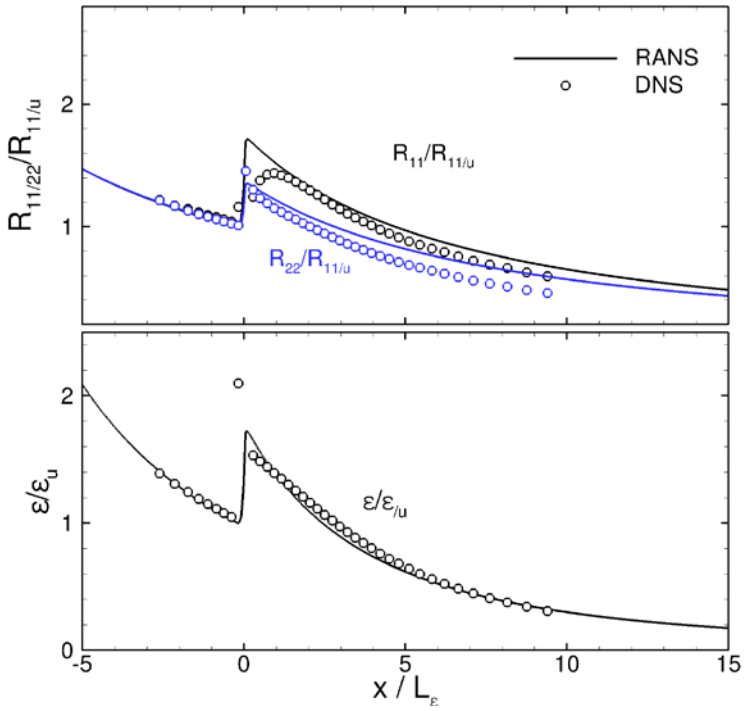
Current work in progress at DLR to improve shock capturing for RSM turbulence model



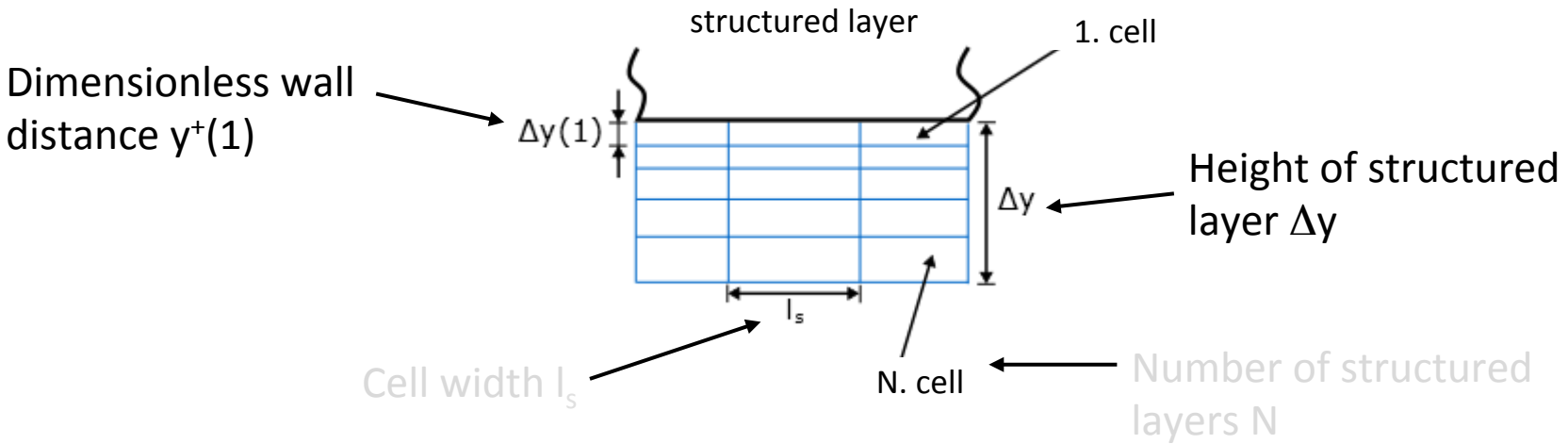
uncorrected



corrected

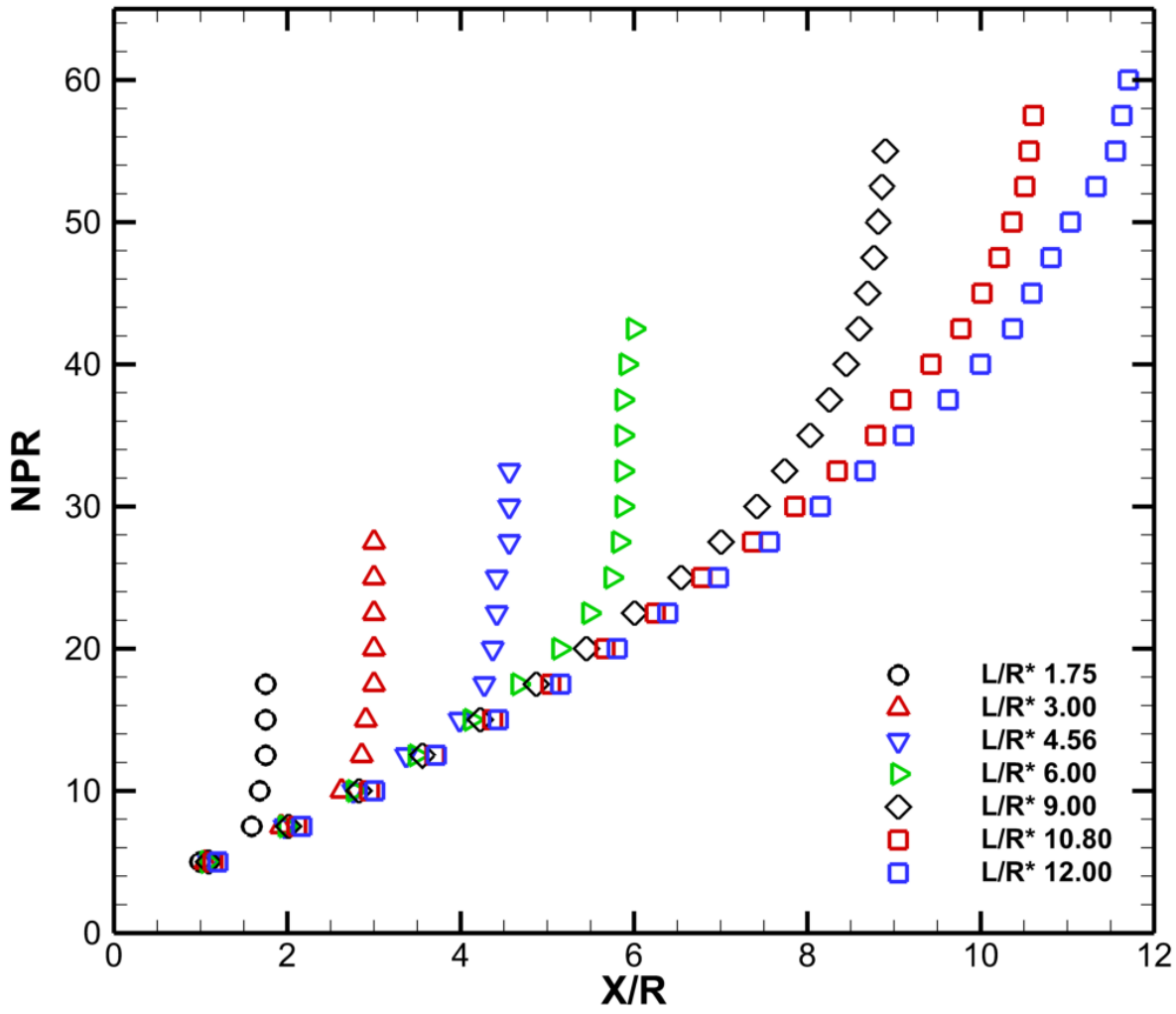


Observed Grid Parameter



Additional Parameters:

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- Influence of turbulence model
- **Influence of flow parameters (NPR, T_0)**
- **Influence of nozzle length**



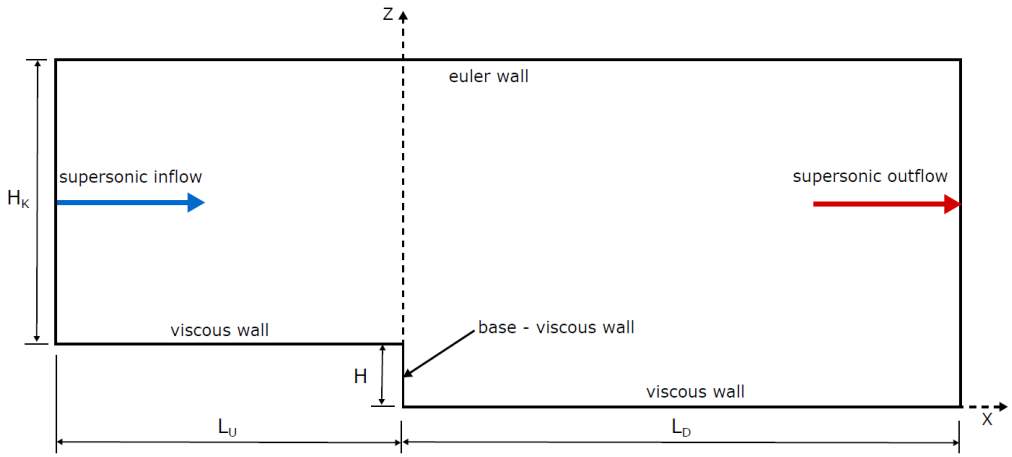
- Separation position follows a linear trend towards nozzle exit
- Influence of truncation on separation position
- For larger L/R* separation occurs later

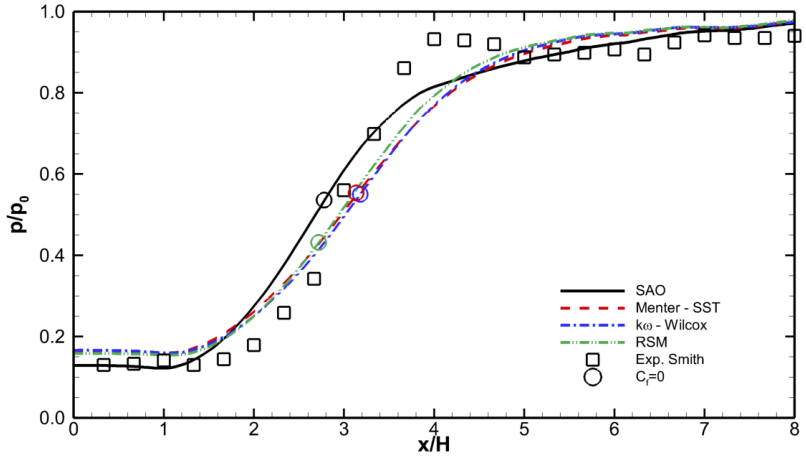
Publication in CEAS Space journal 2016 following soon

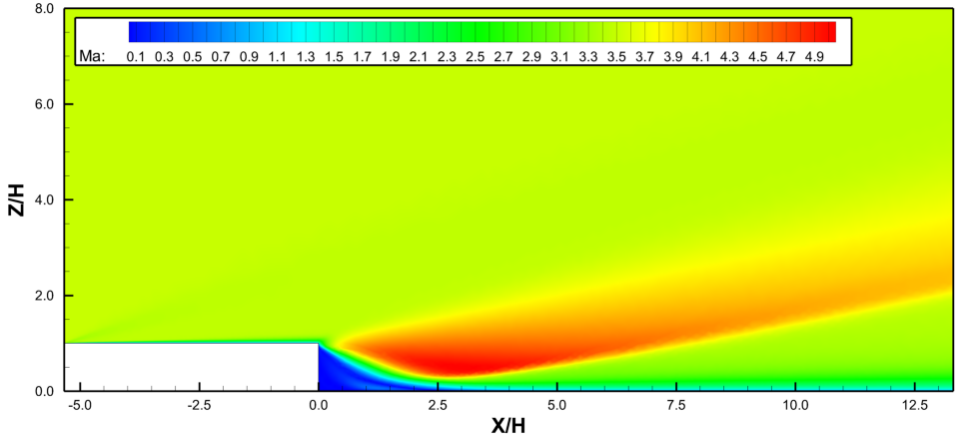
3. Validation

3.3 Backward Facing Step

- Total pressure [bar]: 3.76
- Temperature [K]: 350
- Mach number [-]: 3.5
- Step height [mm]: 19.05

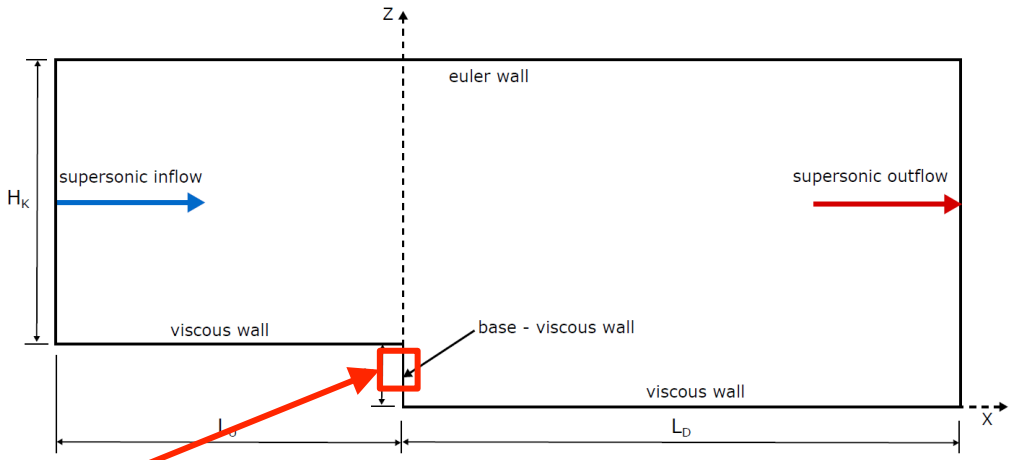


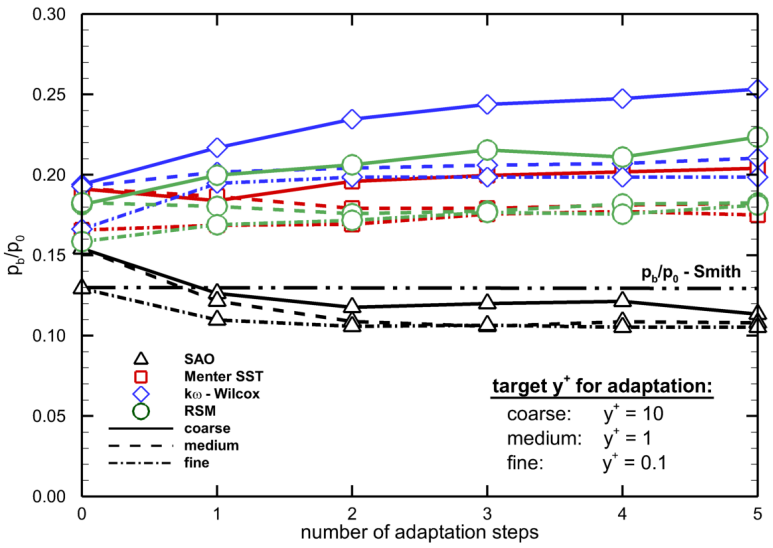




H. E. Smith. The flow field and heat transfer downstream of a rearward facing step in supersonic flow. *Aerospace Research Laboratories. 67-0056, 1967*

- Total pressure [bar]: 3.76
- Temperature [K]: 350
- Mach number [-]: 3.5
- Step height [mm]: 19.05

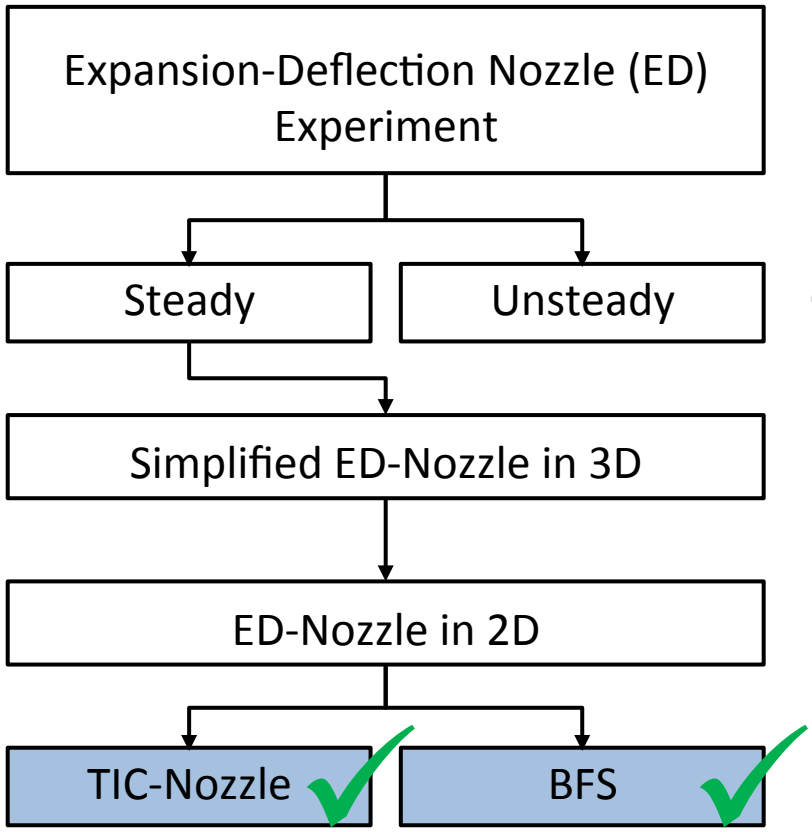




Results of BFS-Study:

- Earlier re-attachment with SAO
- Influence of dimensionless wall distance bigger for 2-equation turbulence models
- Used turbulence models show earlier pressure rise and deficiencies in prediction of reattachment

H. E. Smith. The flow field and heat transfer downstream of a rearward facing step in supersonic flow. *Aerospace Research Laboratories. 67-0056, 1967*



1. Introductionn
2. Numerical Method
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4. The ED-Nozzle
5. Variation of NPR
6. Conclusion

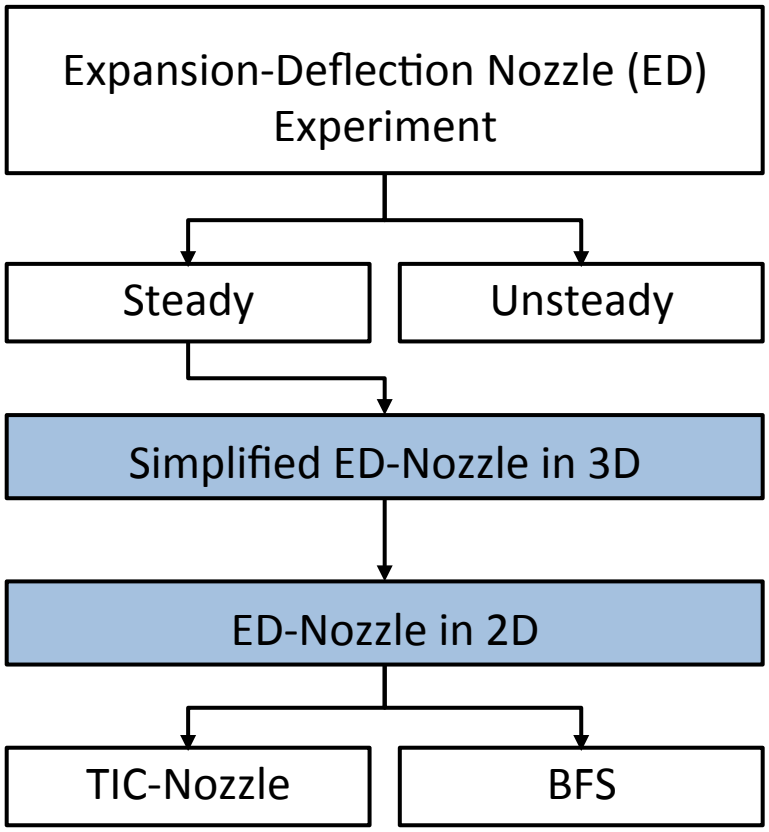
Better understanding of grid parameters on the simulation by comparing simulation results with experimental data

direct applicability

Improves grid generation for ED-nozzle

overall use

Better understanding of the sub-systems results better understanding of the complete system



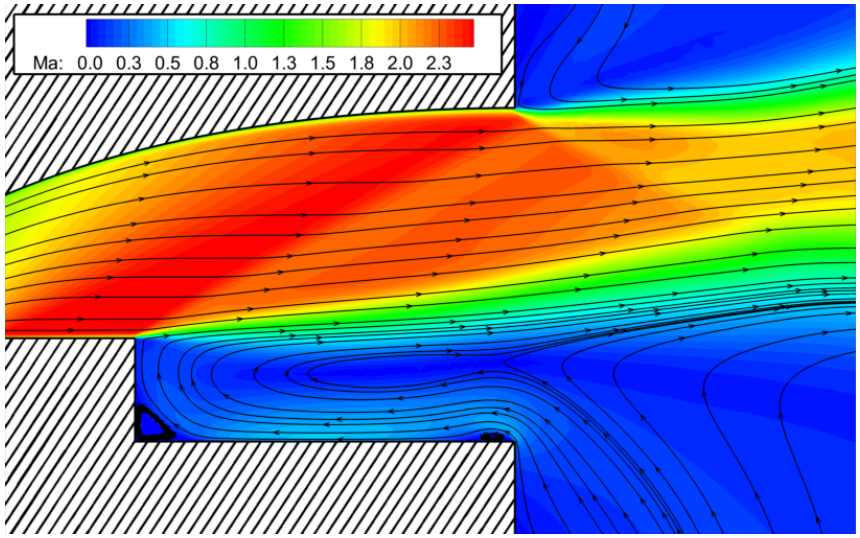
1. Introductionn
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4. The Expansion-Deflection Nozzle (ED)

4.1 Flow Field Description

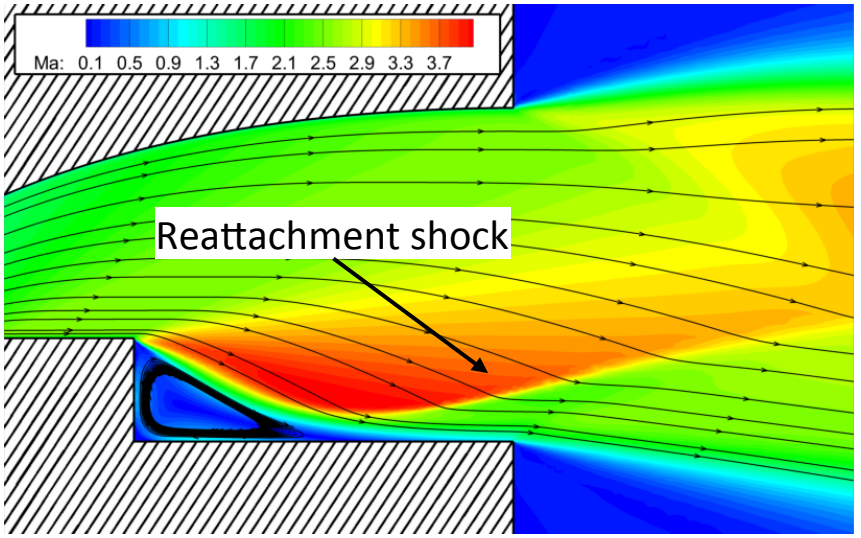
2 operation modes dependent on the nozzle pressure ratio NPR

Open Wake Mode **NPR 9,76**



- Moving shear layer with separation at step
- Open recirculation connected to ambience
- Sub- and supersonic exit flow
- Shear layer separates the two flow regions

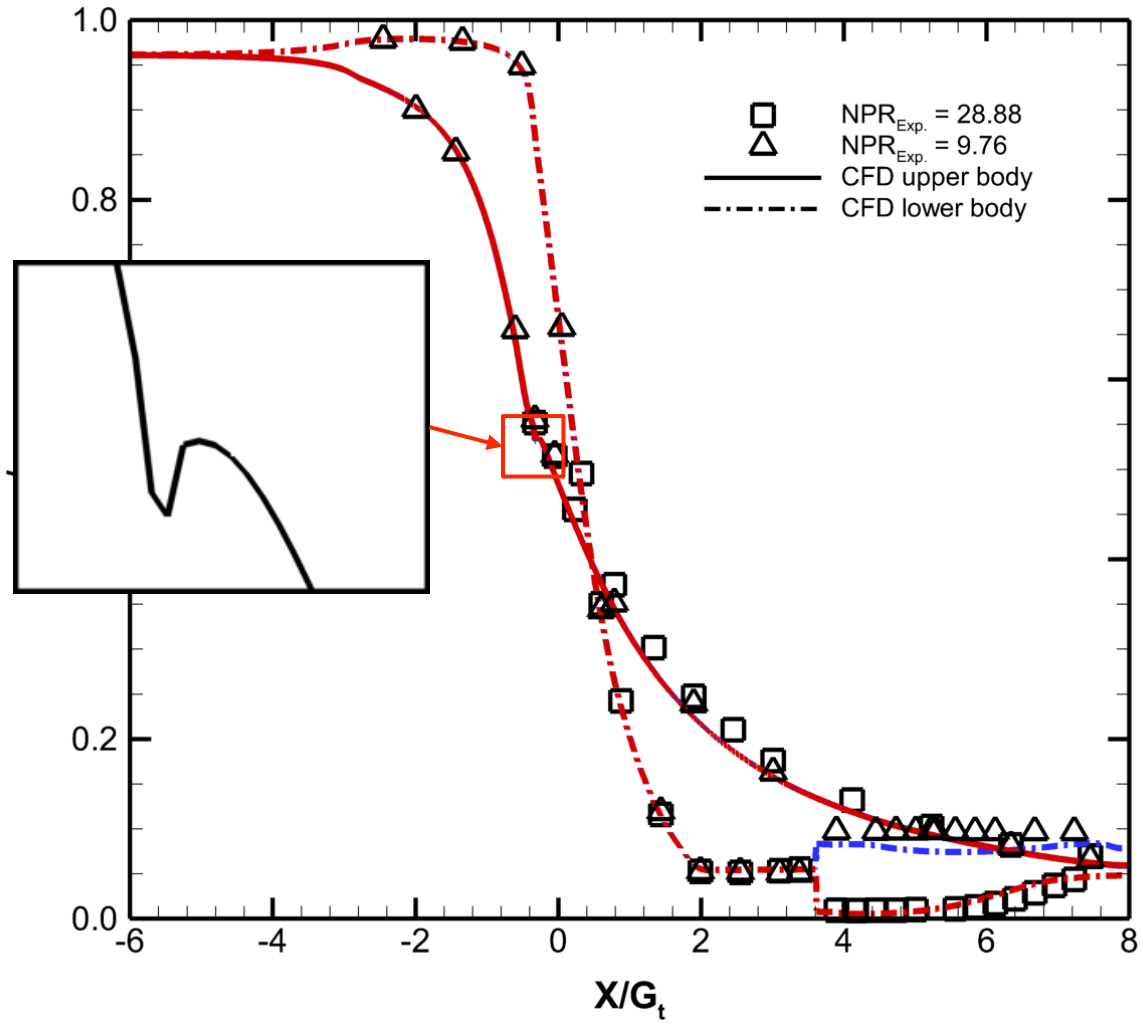
Close Wake Mode **NPR 28,88**



- Moving shear layer deflected towards wake
- Recirculation region separated from ambience
- Reattachment shock
- Full supersonic exit flow

4. The Expansion-Deflection Nozzle (ED)

4.2 Wall Pressure Distribution p/p_a for upper alnd lower wall

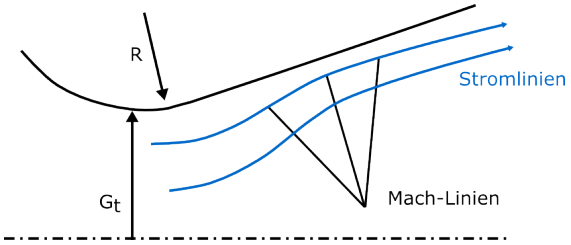


Upper nozzle contour:

- Good agreement with experiments
- 2D and 3D almost identical

Pressure deviation after R*:

- Experimental as well as numerical observed



Over-turning of flow in throat due to small radius

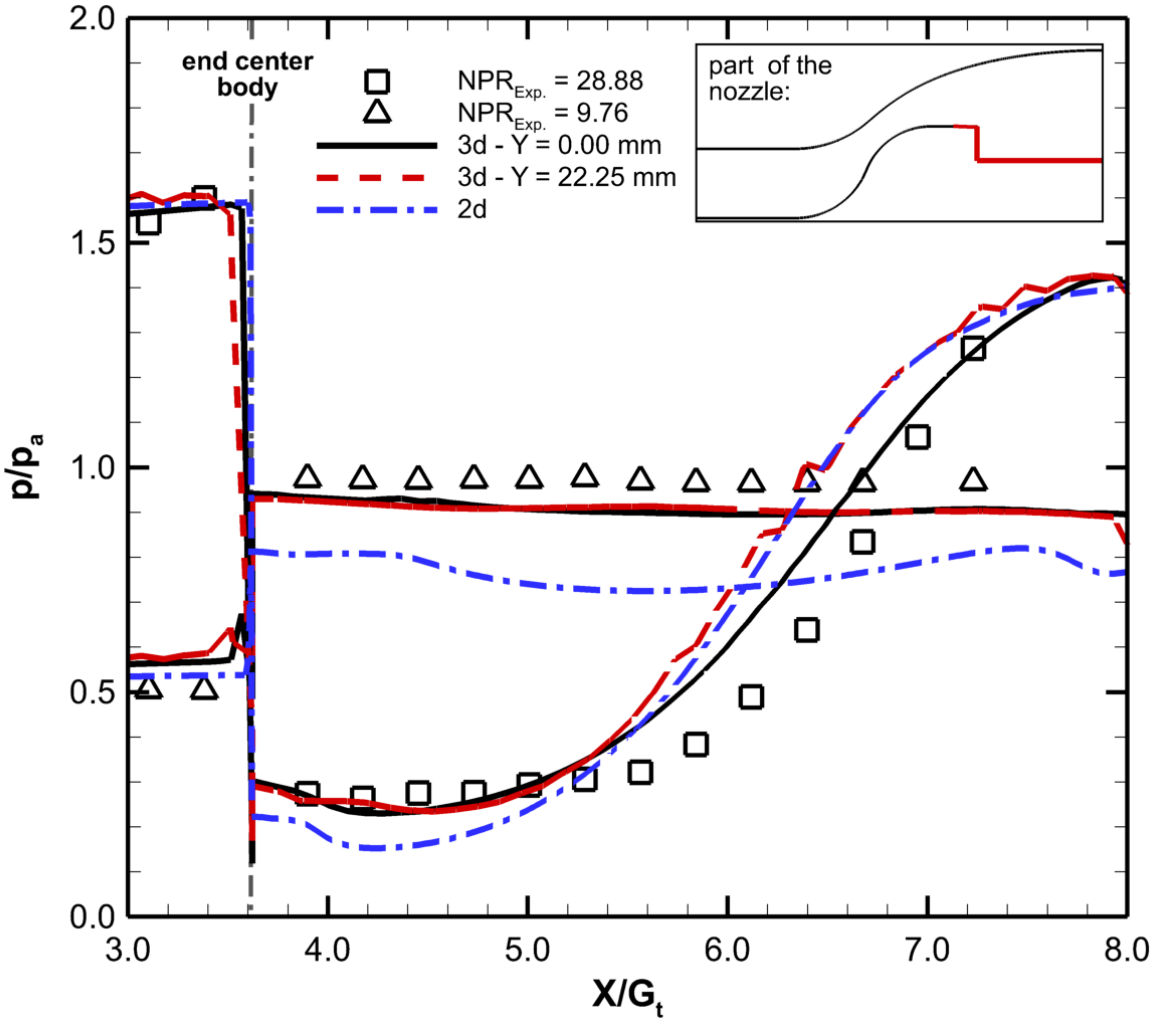
⇩ flow parallel

Expansion

Back, L.H. : Flow Phenomena and Convective Heat Transfer in Conical Supersonic Nozzles

4. The Expansion-Deflection Nozzle (ED)

4.2 Wall Pressure Distribution p/p_a at the nozzle wake



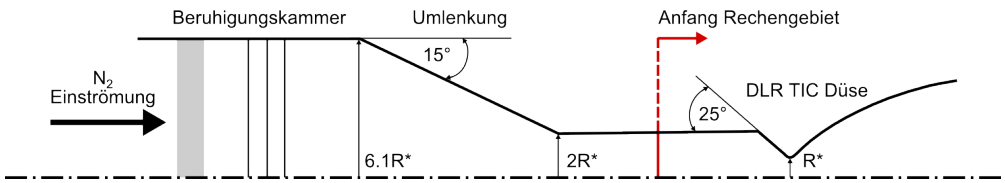
Number of grid cells:

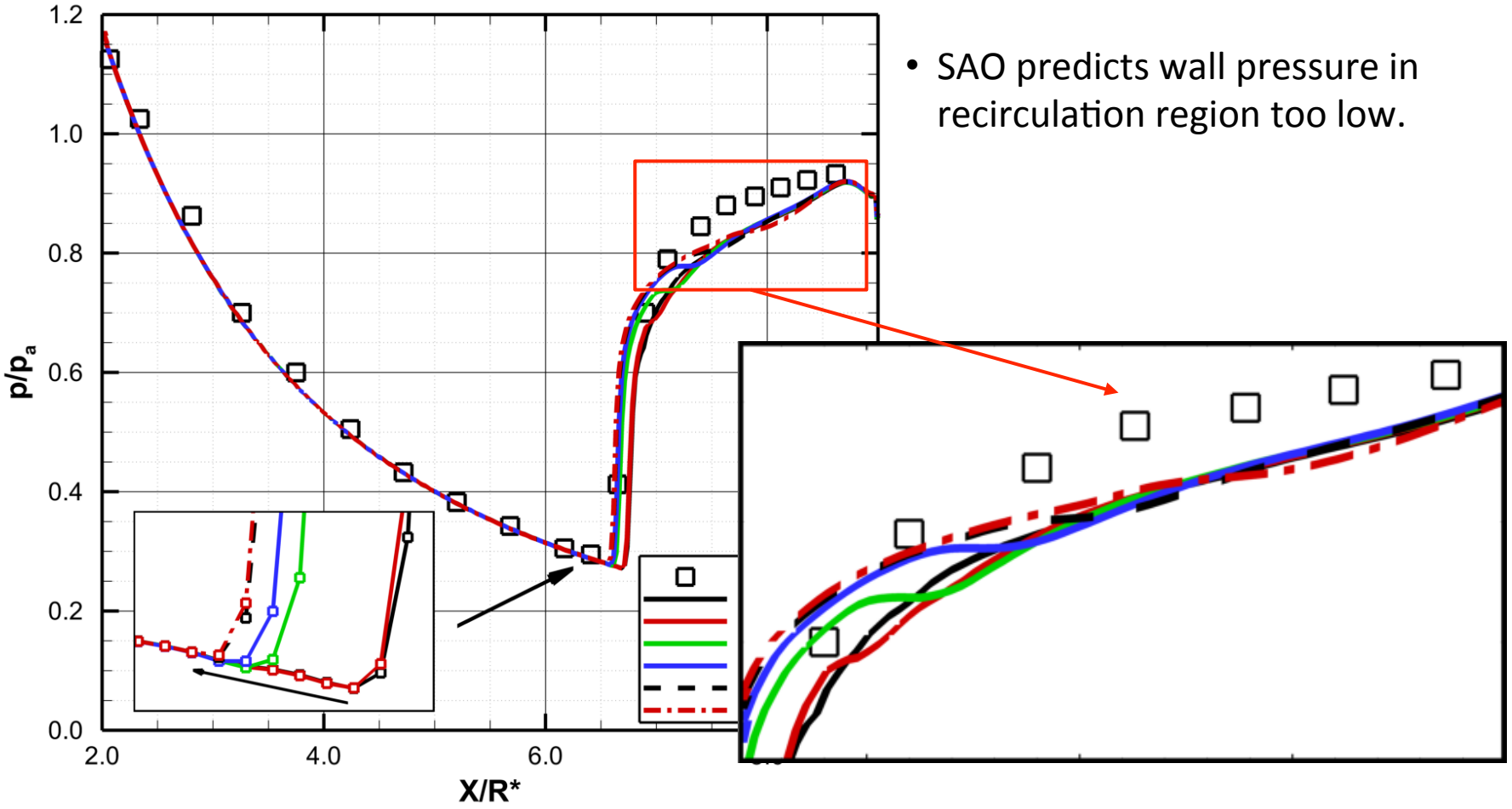
2D: 215 000
3D: 8 900 000

Open wake mode 9.76:

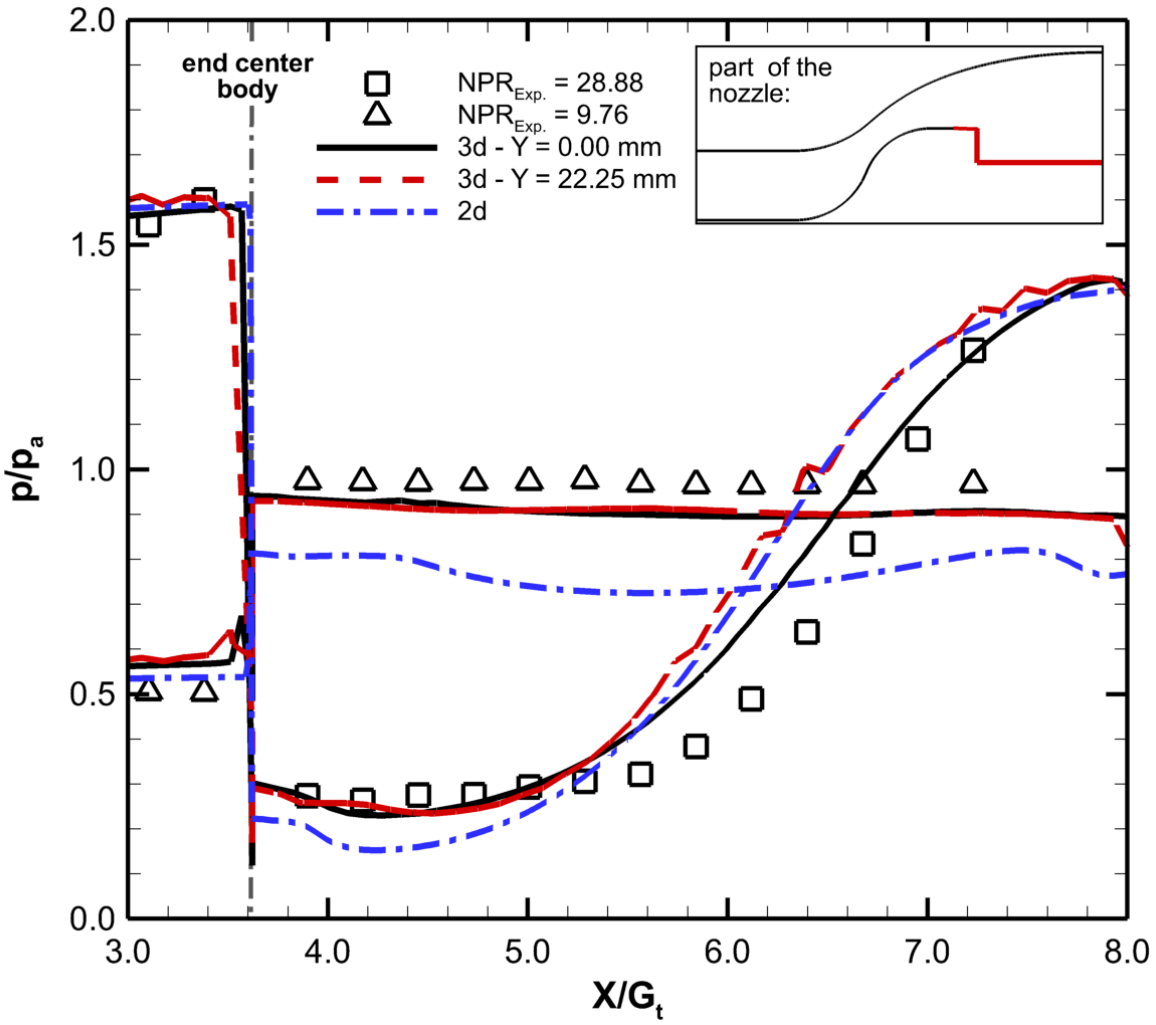
- Poor agreement with wall pressure for 2D and 3D

From validation – Test Case 1A



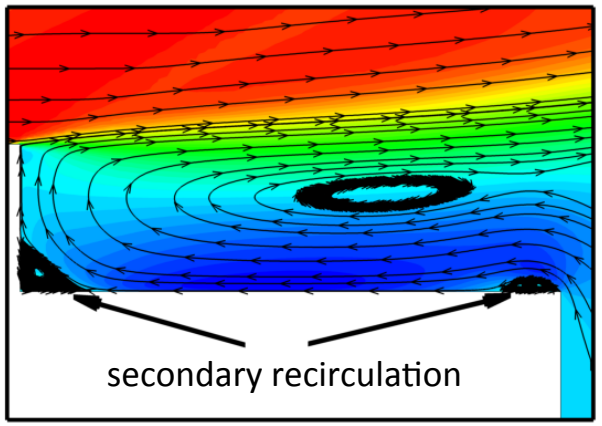


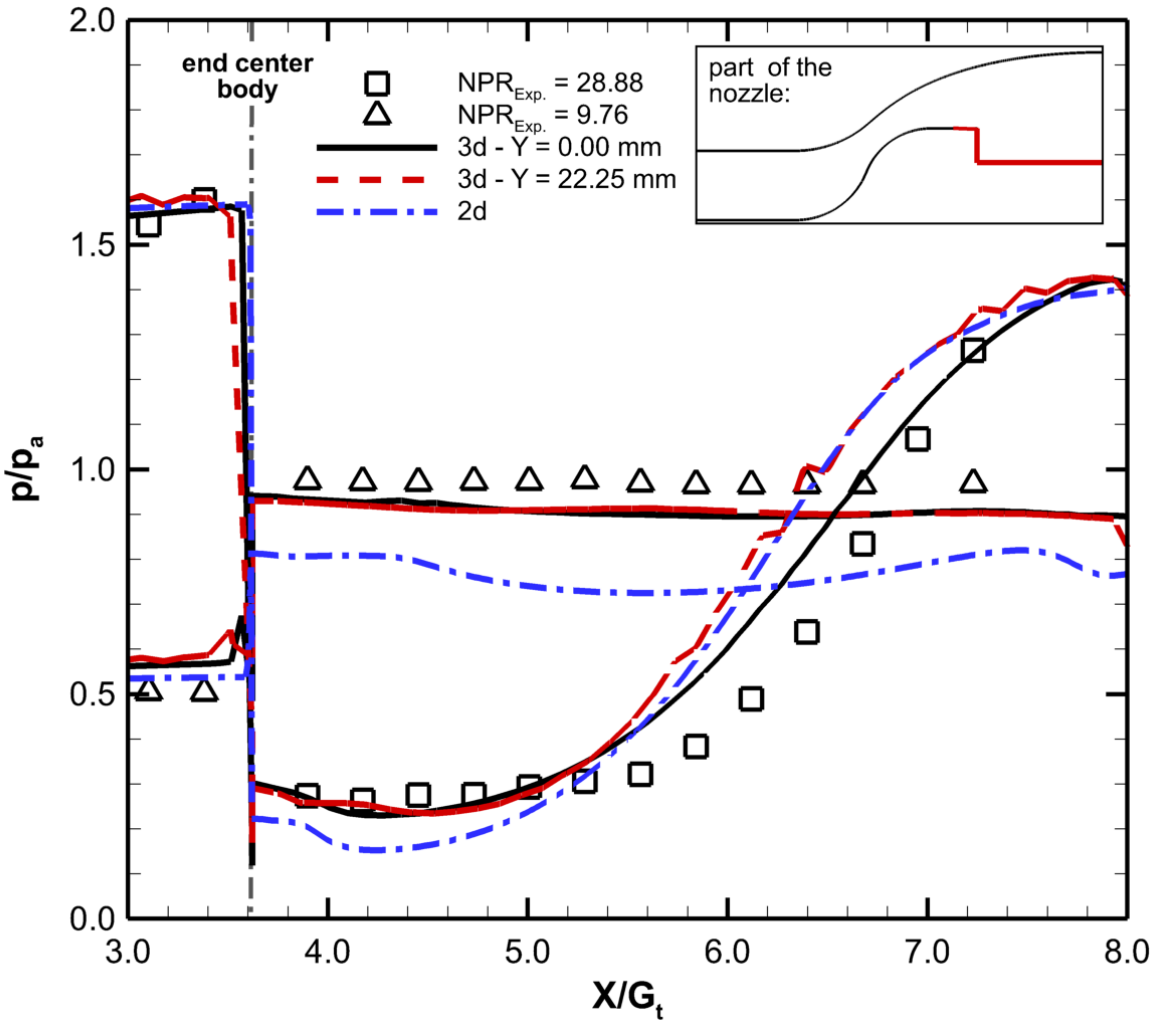
- SAO predicts wall pressure in recirculation region too low.



Open wake mode 9.76:

- Poor agreement with wall pressure for 2D and 3D
- Deviation between 2D and 3D indicates influence of side wall
- Dip in the middle due to secondary recirculations





Open wake mode 9.76:

- Poor agreement with wall pressure for 2D and 3D
- Deviation between 2D and 3D indicates influence of side wall
- Dip in the middle due to secondary recirculations

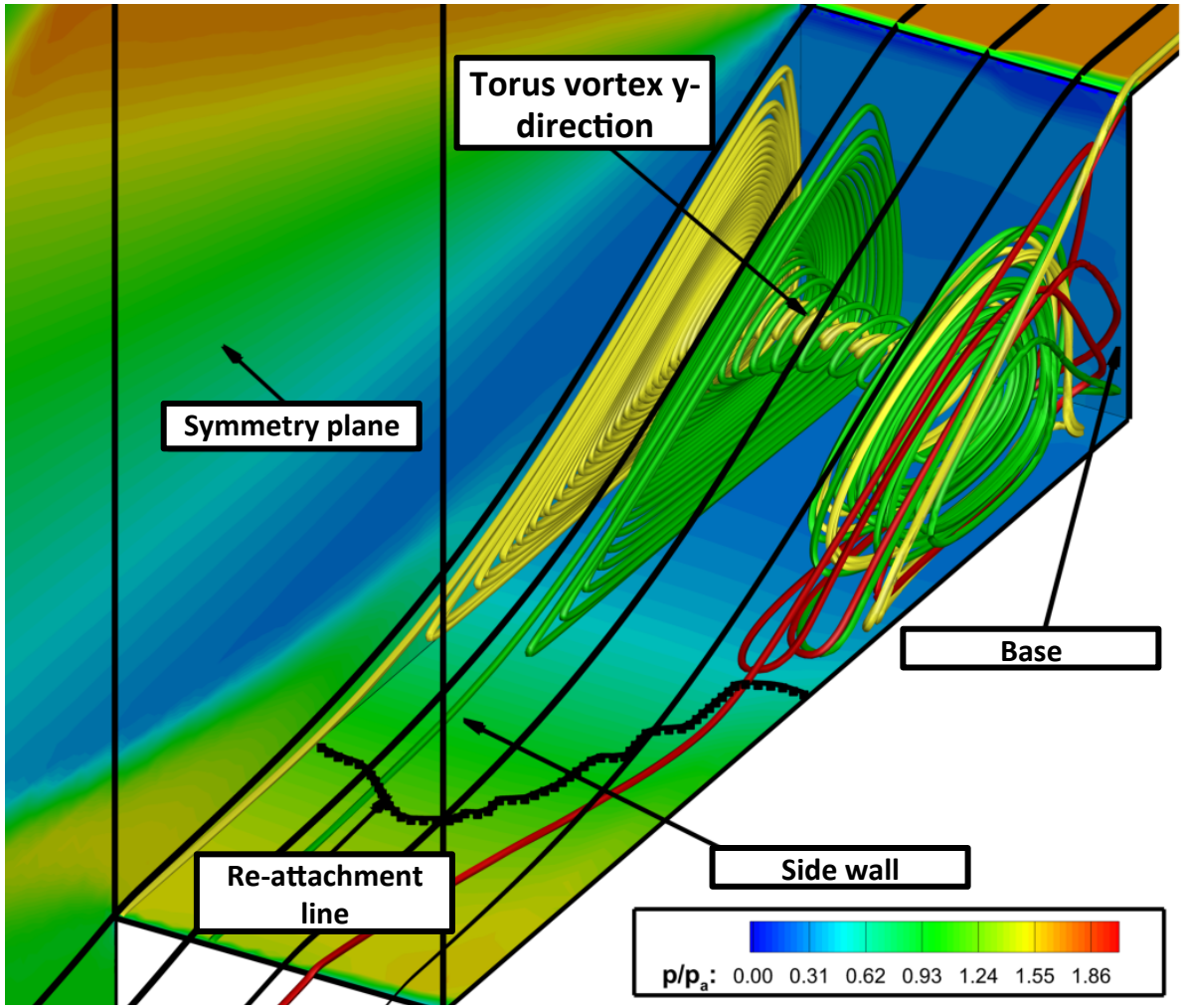
Closed wake mode 28.88:

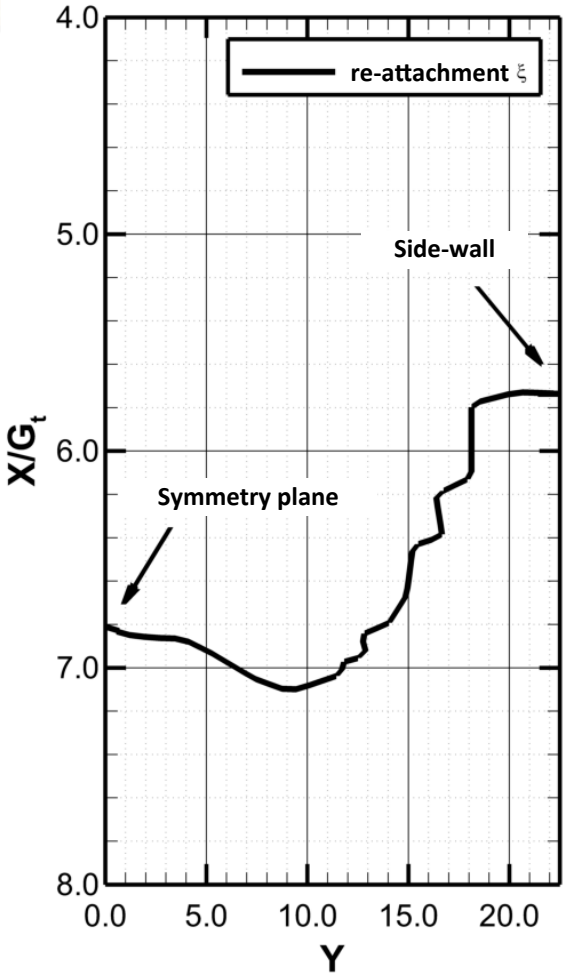
- Deviation 2D and 3D smaller
- Acceptable agreement of wall pressure in recirculation region for 3D
- Re-attachment to early
  → pressure increases to early
- Premature re-attachment close to the side wall



4. The Expansion-Deflection Nozzle (ED)

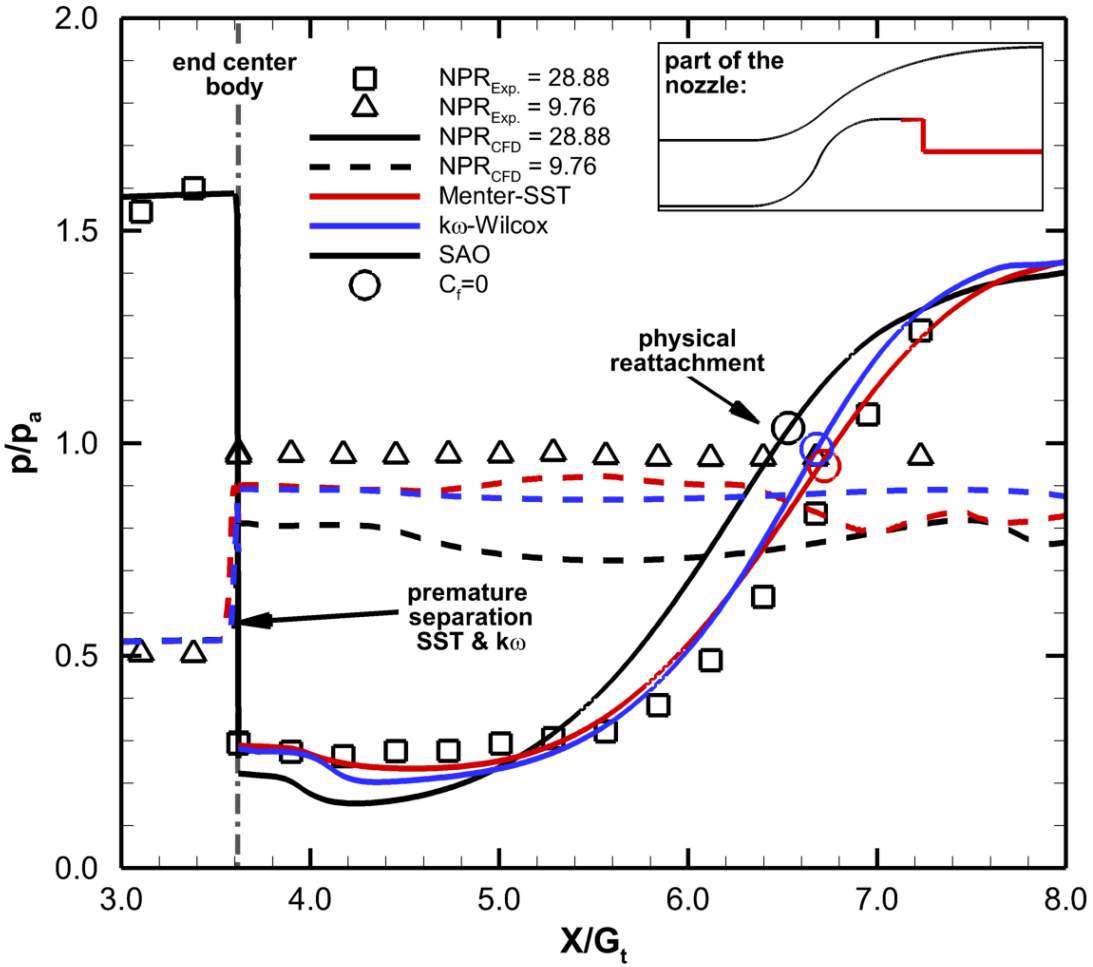
4.3 Re-attachment of shear layer at central body

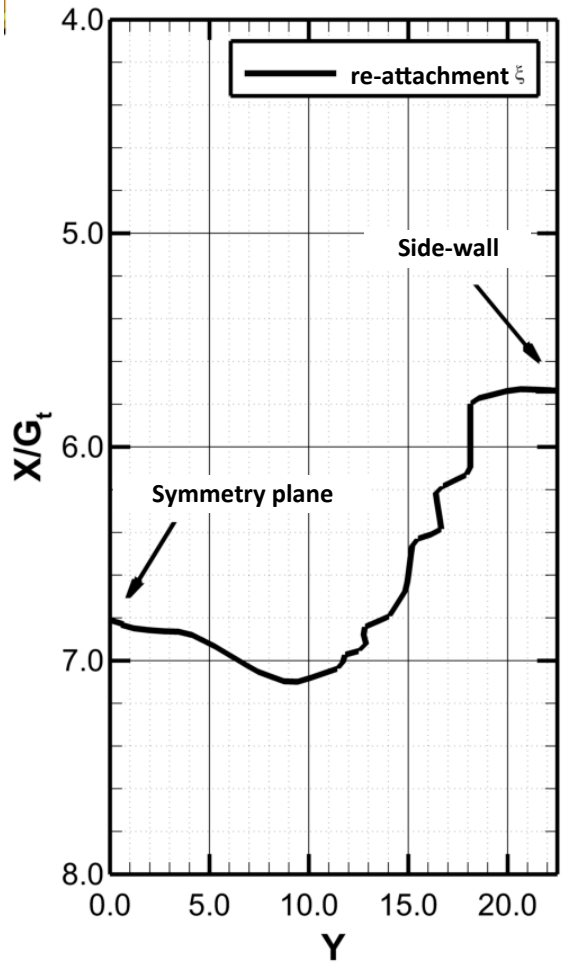


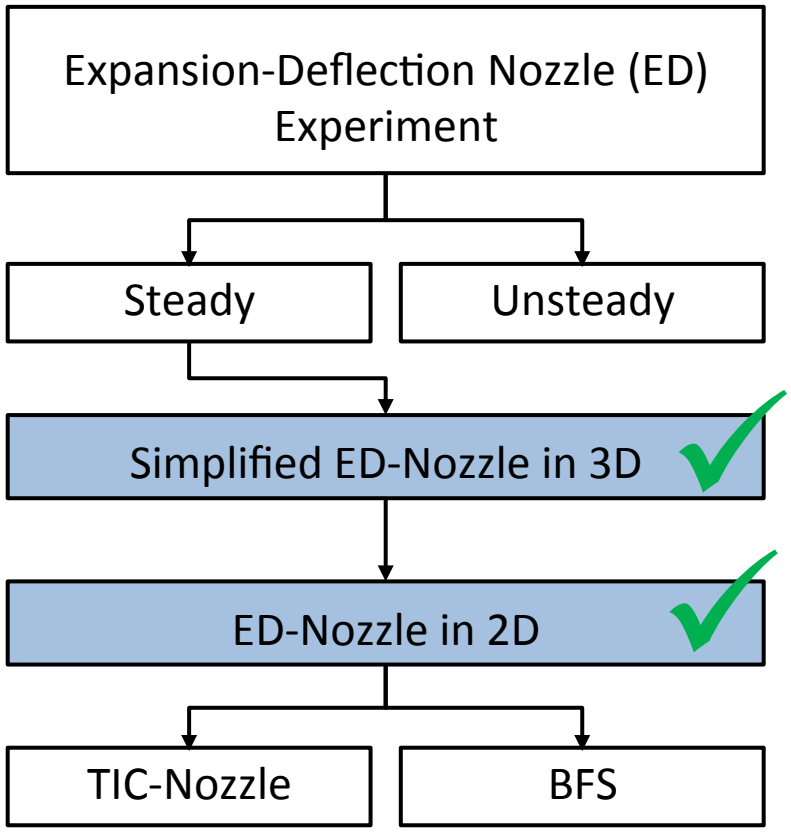


4. The Expansion-Deflection Nozzle (ED)

4.4 Wall pressure for different turbulence models (2D)



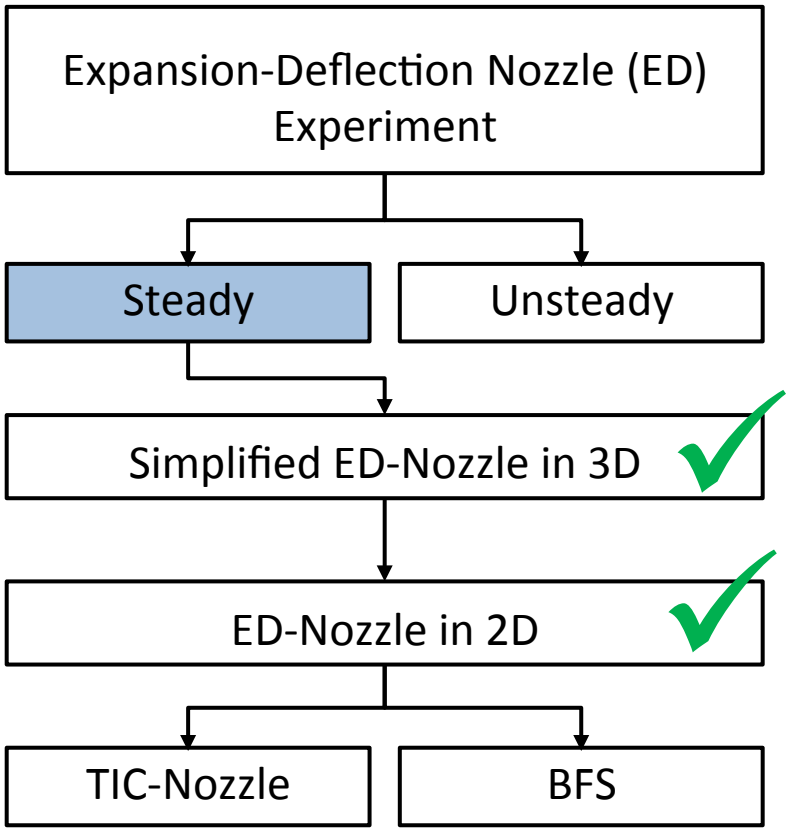




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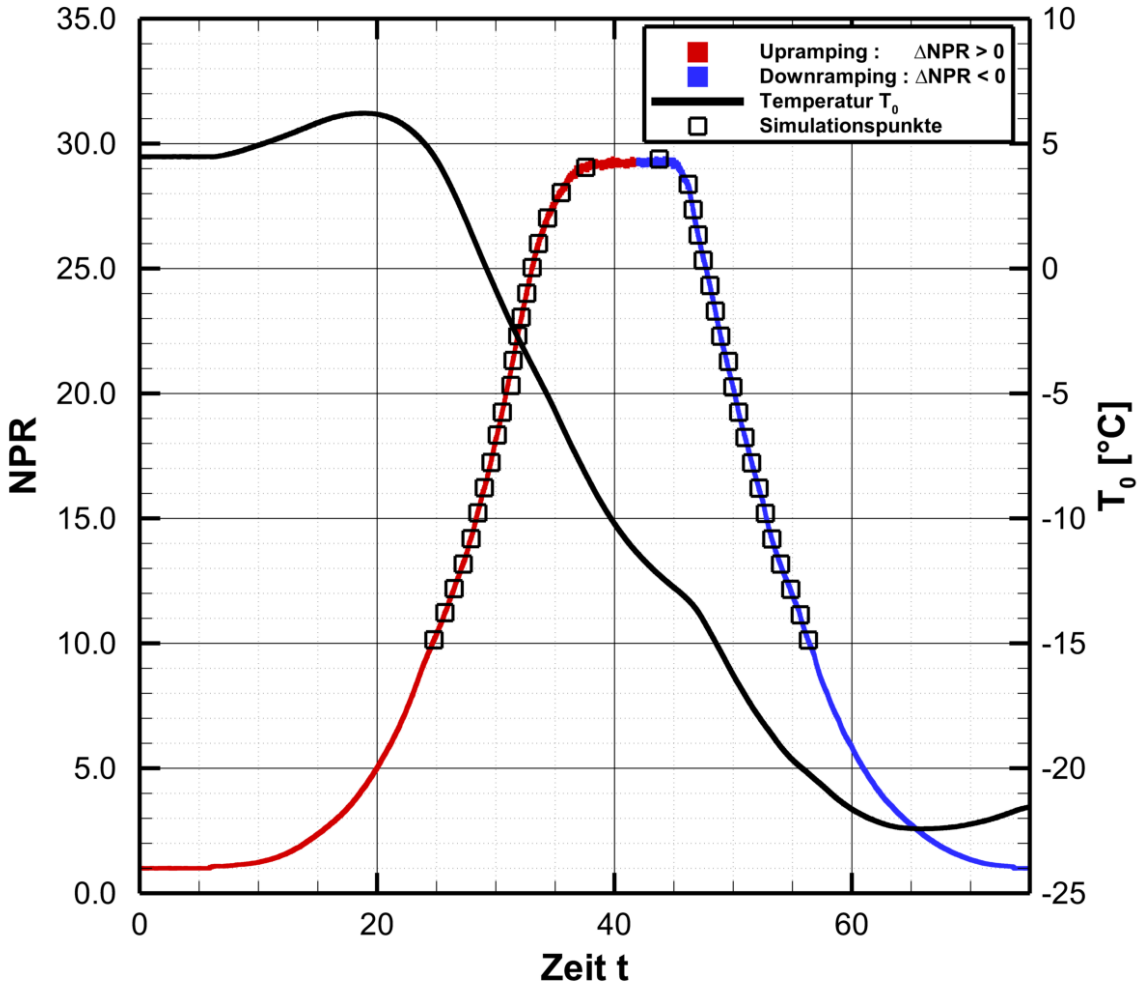
2D simulation gives a good first impression on the two different operation modes

Simplified 2D assumption not sufficient, 3D simulation necessary to capture side-wall effects



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Transient pressure ramp from experiments simulated with 72 stationary computations



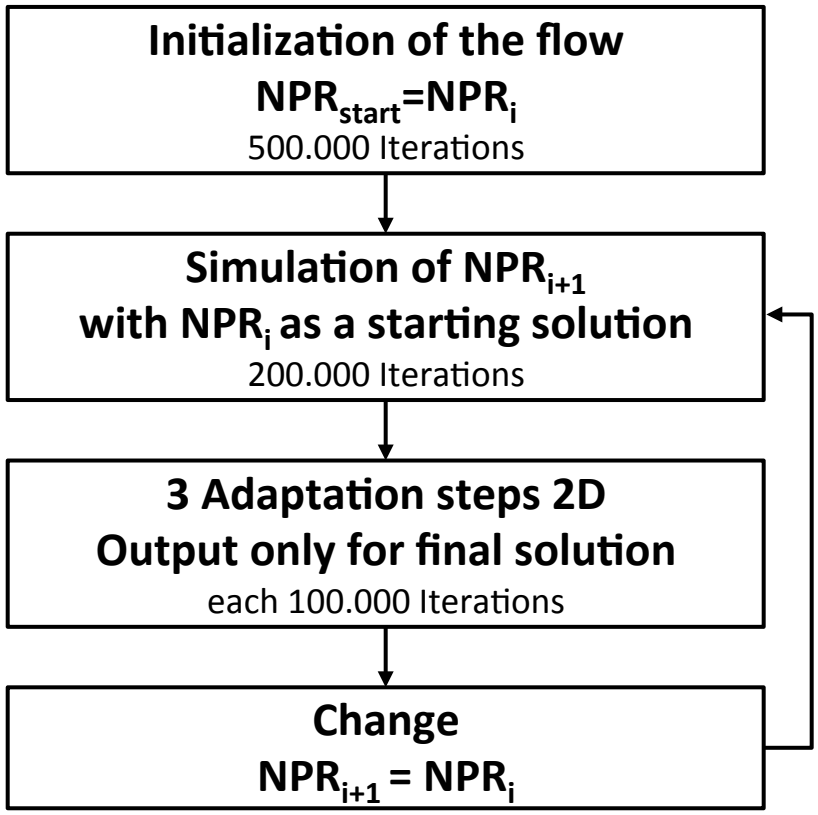
Upramping: $\frac{d(NPR)}{dt} > 0$

Downramping:: $\frac{d(NPR)}{dt} < 0$

- Inflow and ambient conditions from simulations match experiments
- Upramping and Downramping were simulated seperately
- Pressure variation of 0.5 in the transition region.

5. Variation of Nozzle Pressure Ratio (NPR)

5.1 Numerical method and transient pressure ramp



Grid resolution:

2D: 215.000 (500.000 after adaptation)
3D: 7.9000.000 (no adaptation)

Iterations for stationary pressure ramp:

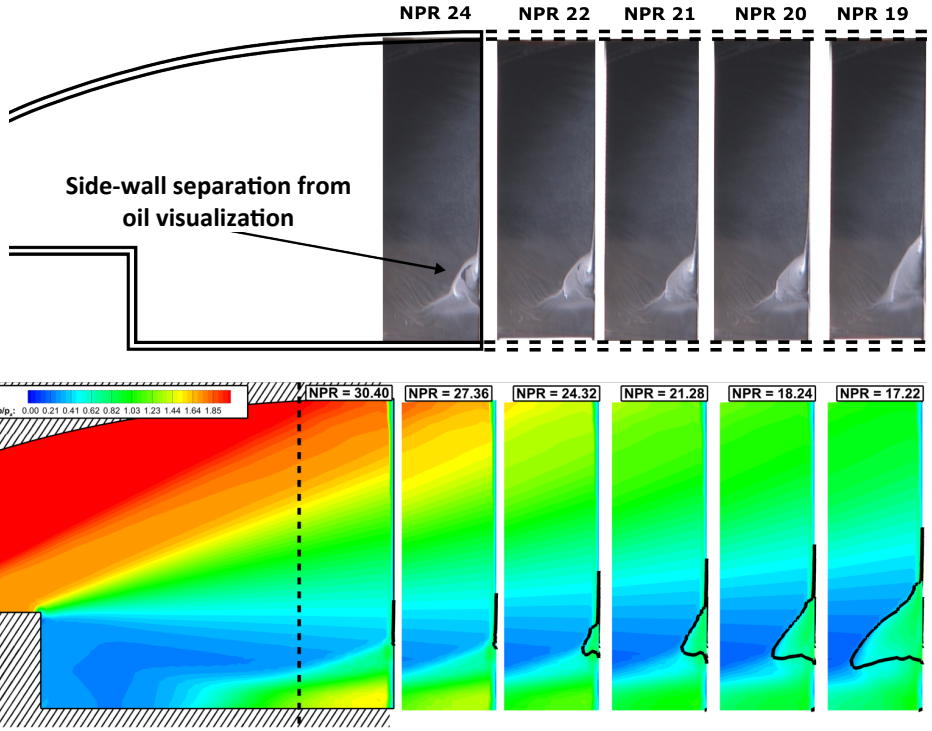
2D: 21.000.000 Iterations (3 x adapted)
3D: 11.000.000 Iterations

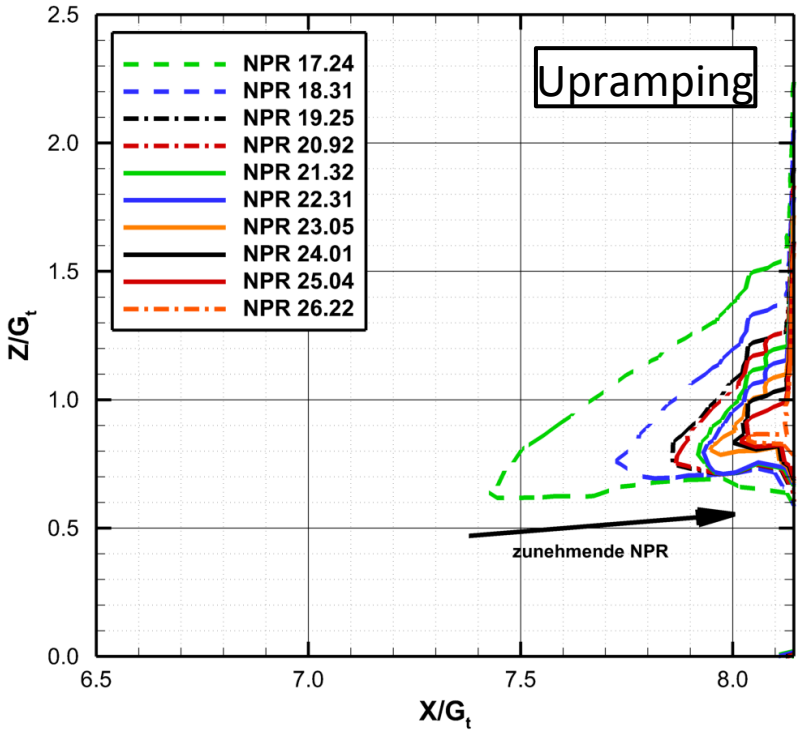
Computational Time and resources:

- DLR student Cluster laraserv01 (64 Cores)
- Each 2D-Simulation ~14 days
- Each 3D-Simulation ~90 days

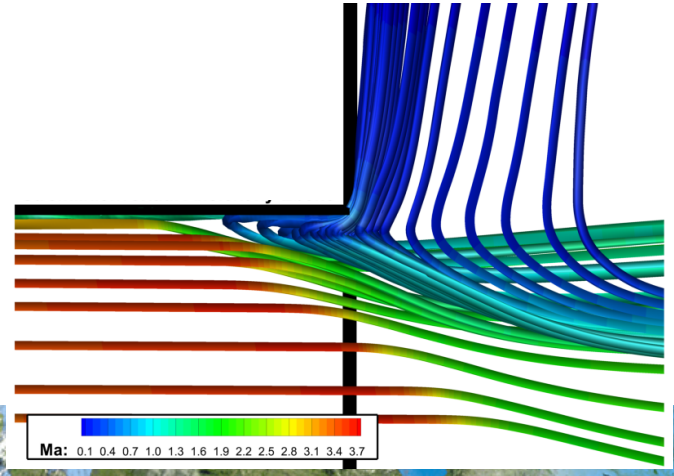
5. Variation of Nozzle Pressure Ratio (NPR)

5.2 Side-wall separation in off-design





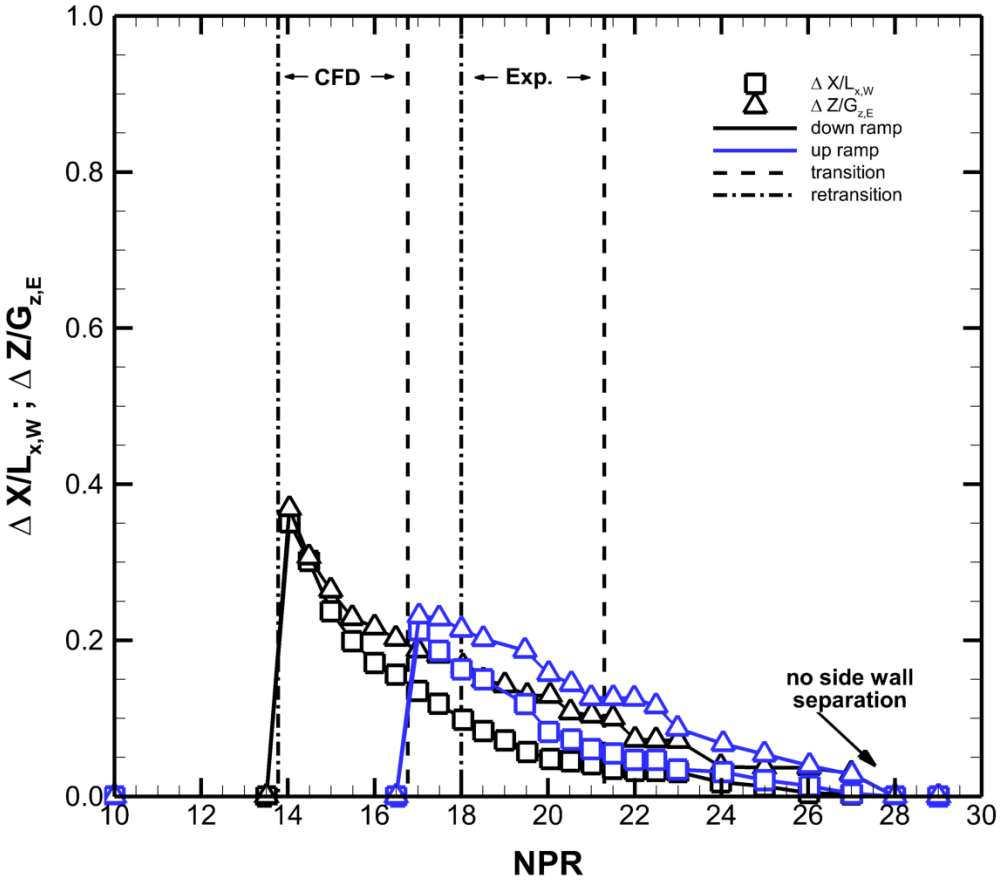
- Side-wall separation in off-design
- No side-wall separation for design pressure of NPR 30
- Separation above re-attachment shock



5. Variation of Nozzle Pressure Ratio (NPR)

5.2 Side-wall separation in off-design

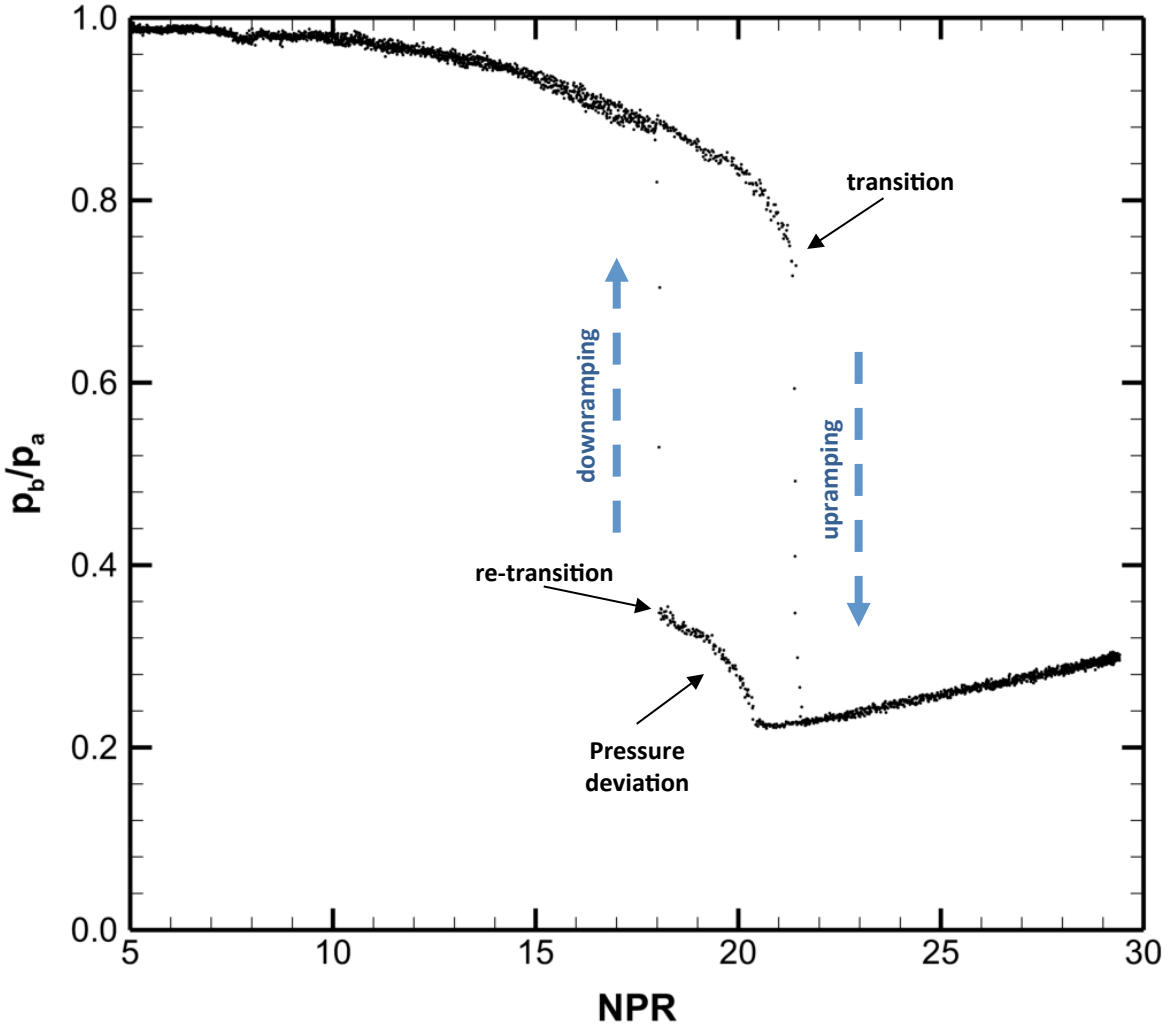
- Qualitative picture from experiments (right)
- Separation position only from CFD
- As discussed, transition at lower NPR
- Stronger numerical side wall separation then experimentally expected (due to later separation)

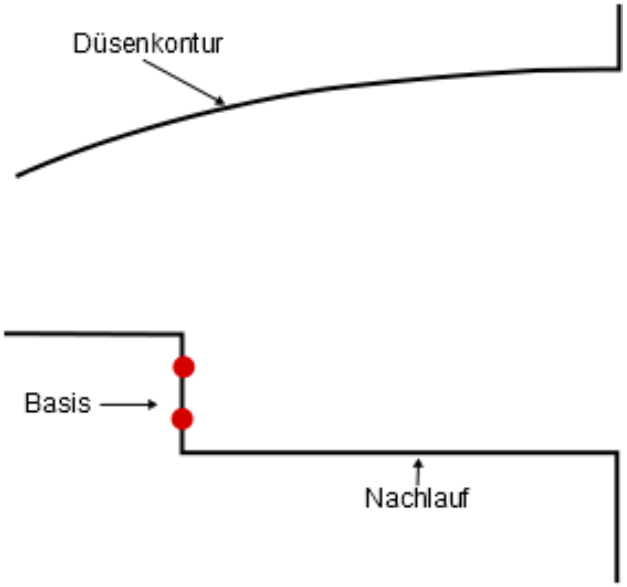


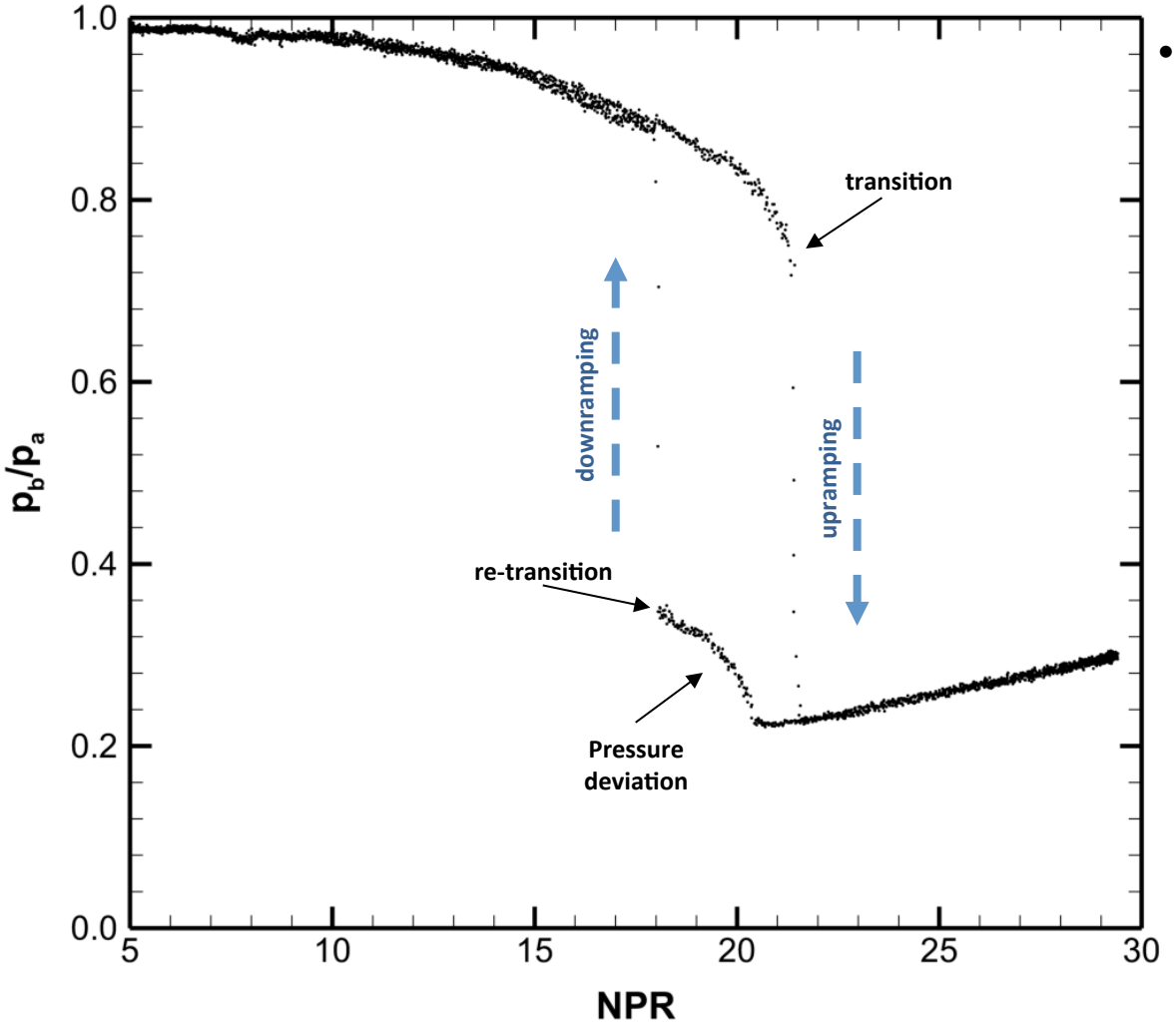


5. Variation of Nozzle Pressure Ratio (NPR)

5.3 Hysteresis behaviour







- Hysteresis effect:
  Transition depends on NPR and rate of change of NPR

assumption

Pressure deviation due to side wall separation

⇩

Numerics capture the side wall separation

conclusion

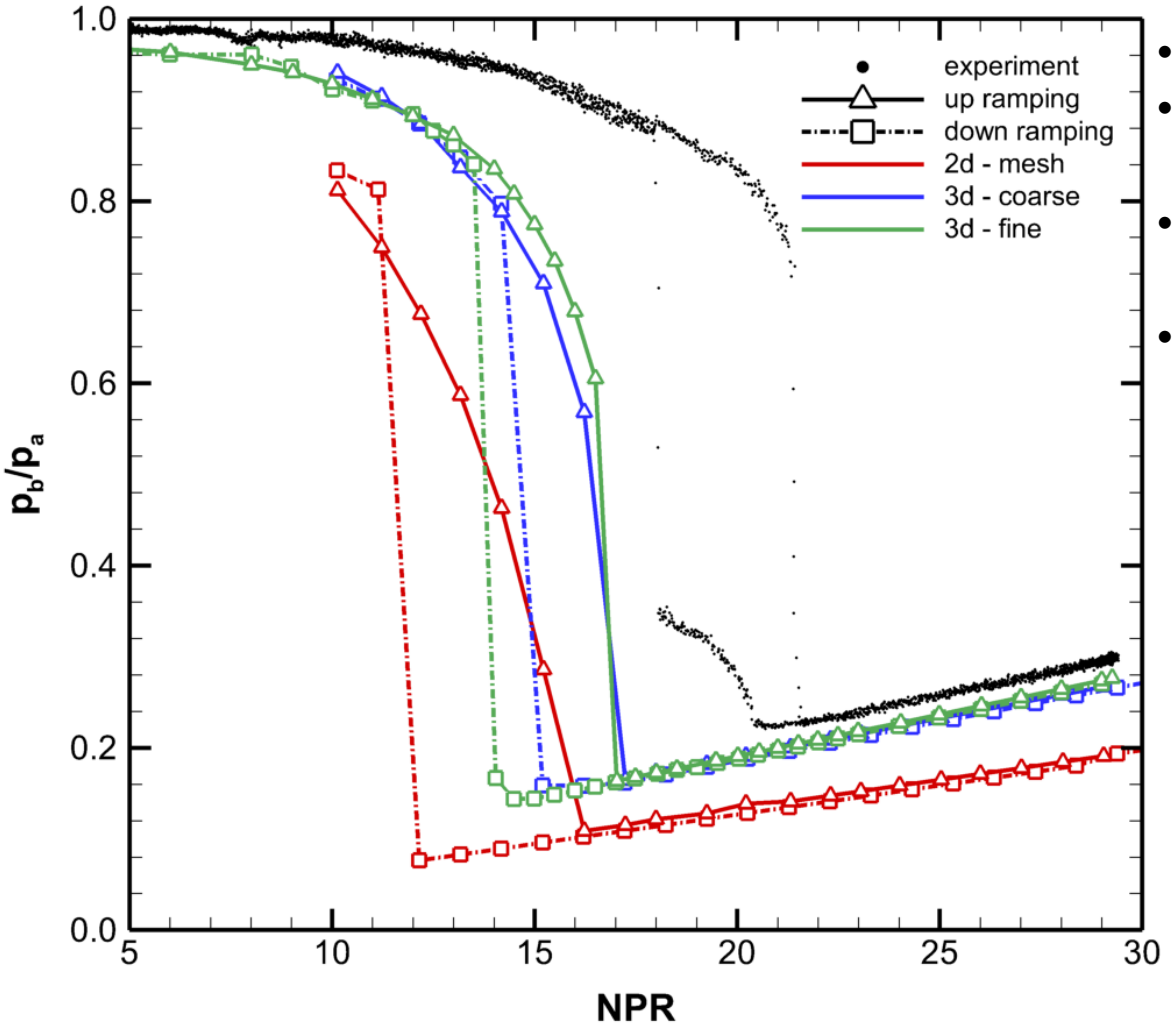
⇩

Numerics should capture the deviation



5. Variation of Nozzle Pressure Ratio (NPR)

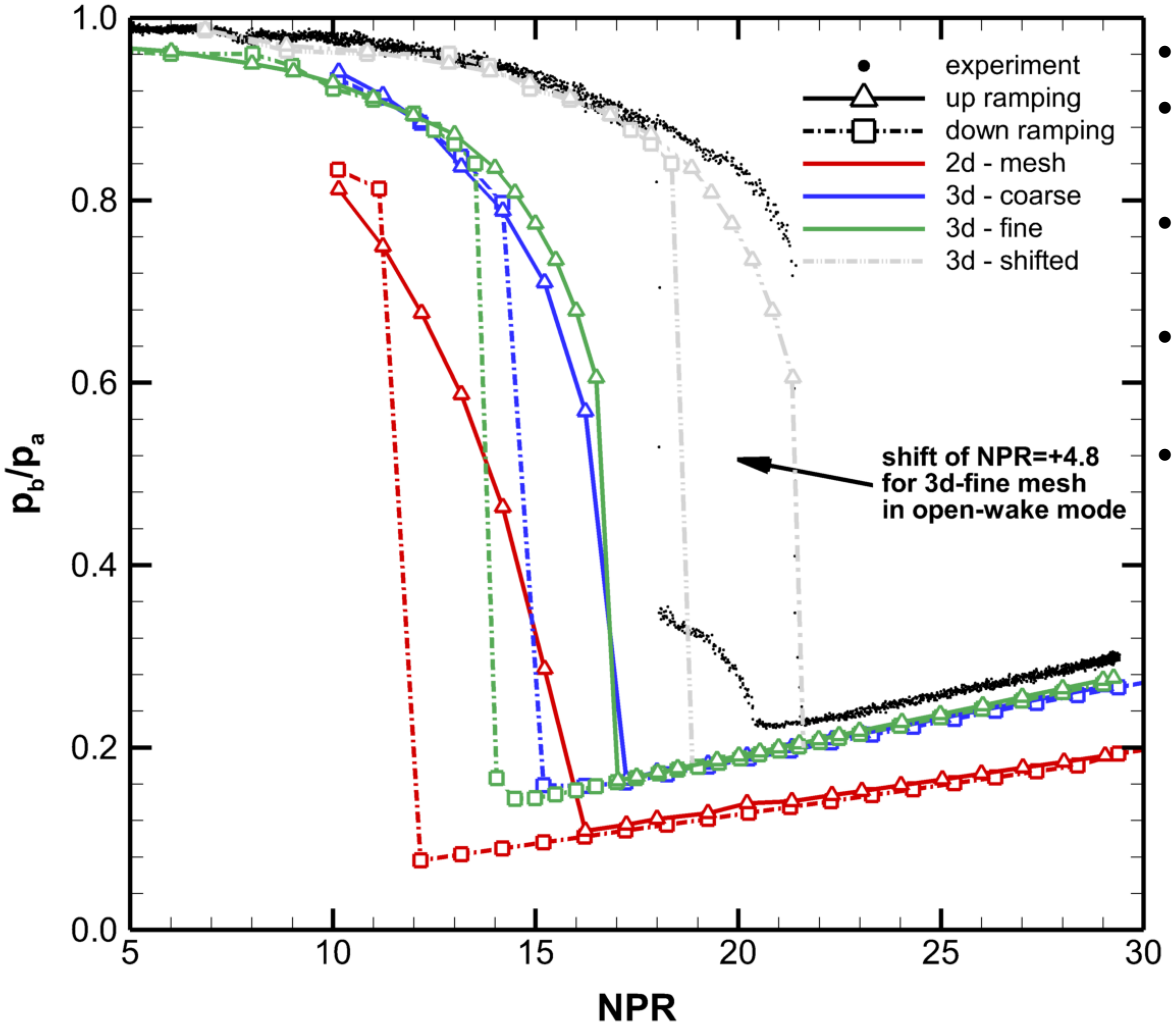
5.3 Hysteresis behaviour



- Hysteresis effect
- Base pressure too low in open wake mode
- Transition shifted towards lower Nozzle Pressure Ratios (NPR)
- Deviation not captured

5. Variation of Nozzle Pressure Ratio (NPR)

5.3 Hysteresis behaviour

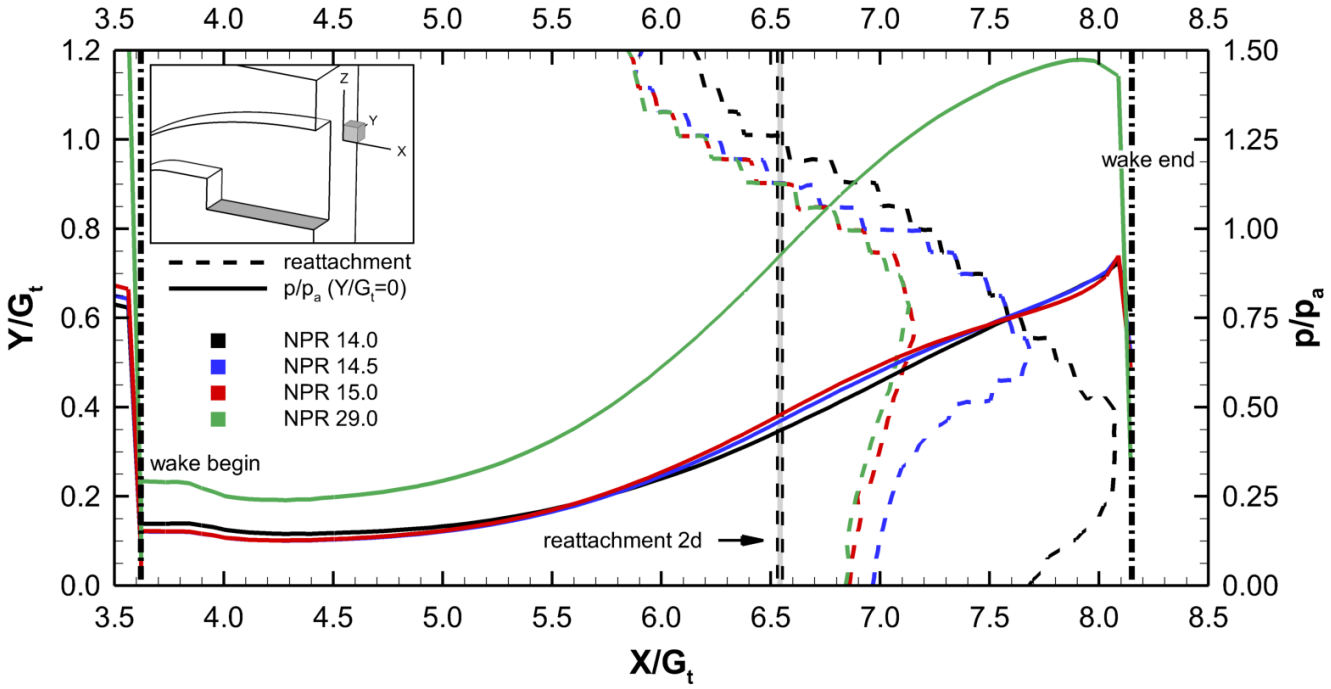


- Hysteresis effect
- Base pressure too low in open wake mode
- Transition shifted towards lower Nozzle Pressure Ratios (NPR)
- Deviation not captured

- Trend well captured

5. Variation of Nozzle Pressure Ratio (NPR)

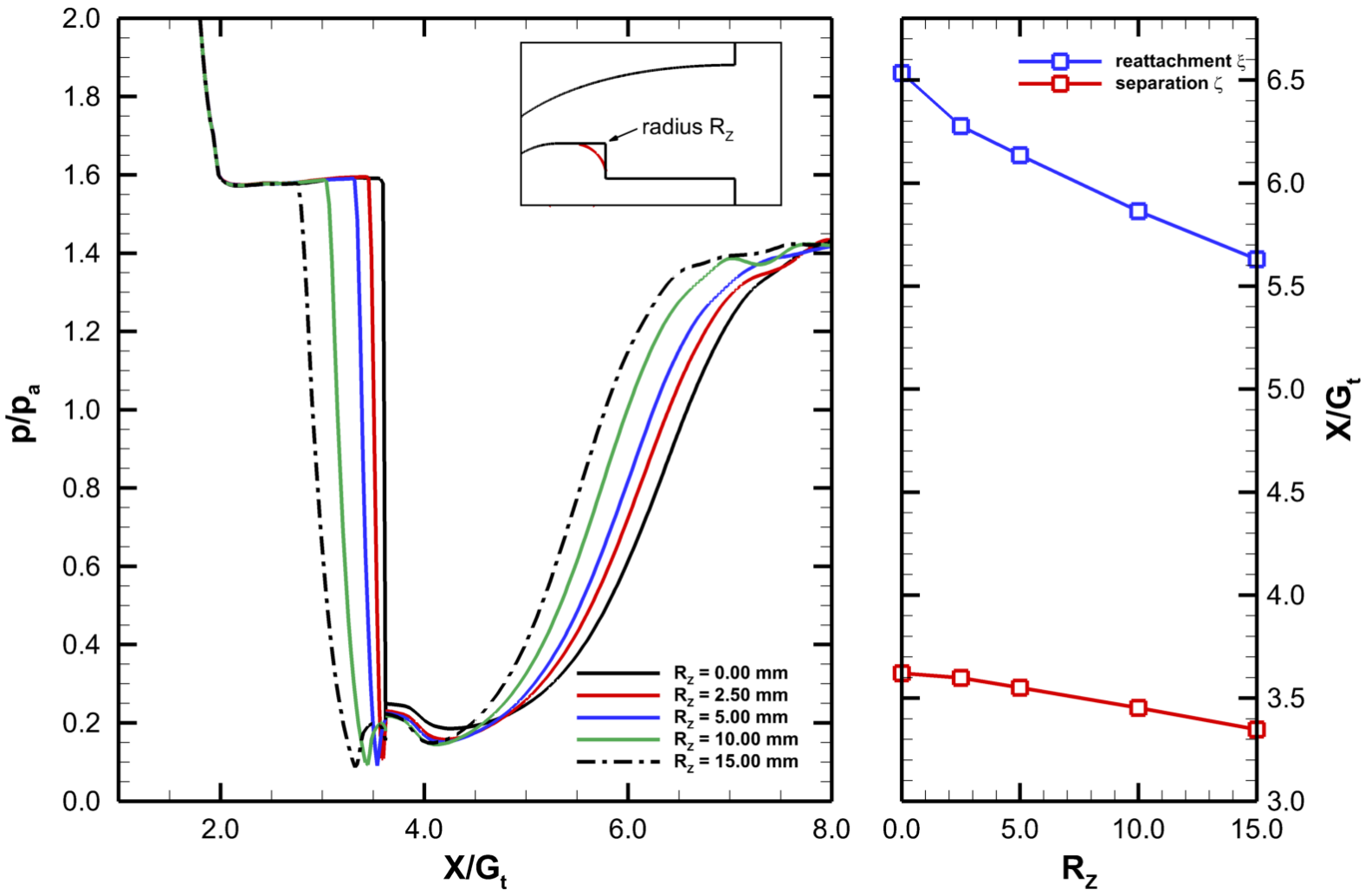
5.4 Re-attachment on central body

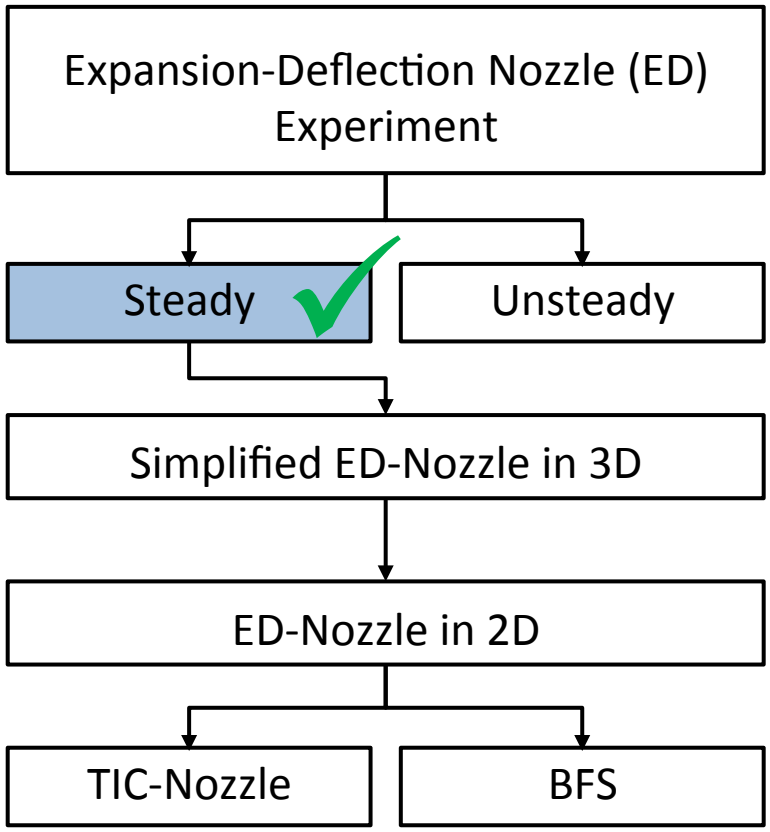


- 3D shape of re-attachment line
- Defined by c_f=0
- For low NPR close to the nozzle End

5. Variation of Nozzle Pressure Ratio (NPR)

5.5 Outlook – variation of nozzle geometrie

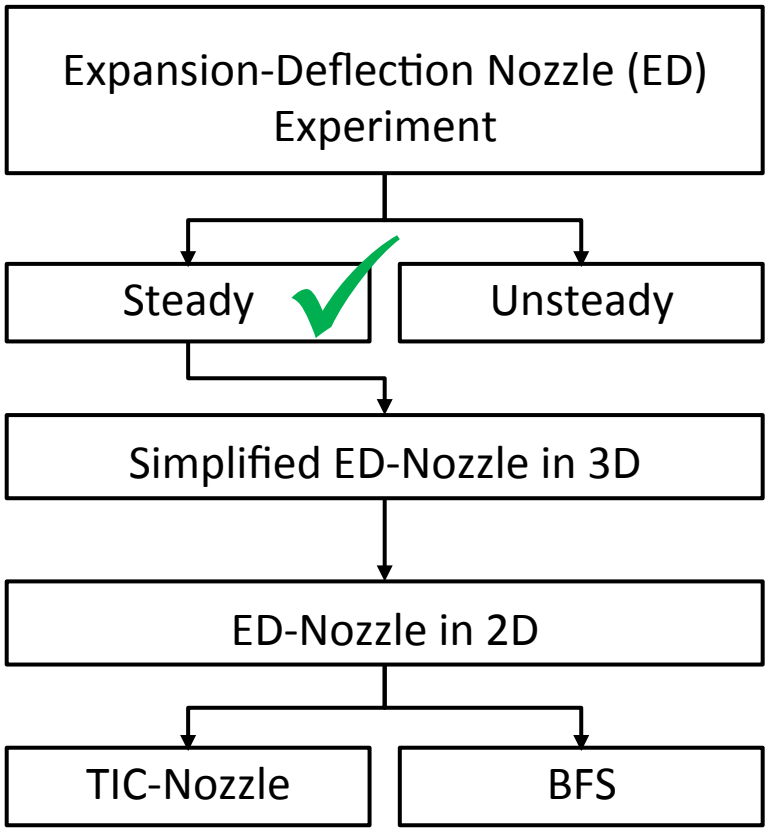




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Side-wall separation in off-design could be captured by numerics

Hysteresis behavior could be shown, however the pressure deviation needs further observation



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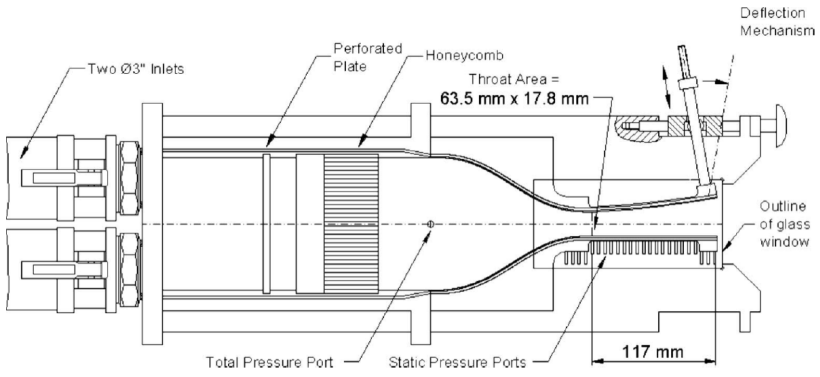
6. Conclusion

- **Validation strategy with backward facing step and separated nozzle flow**
  - Base pressure prediction for SAO very good
  - Pressure rise due to reattachment shock too early
  - Good separation and shock system again for SAO

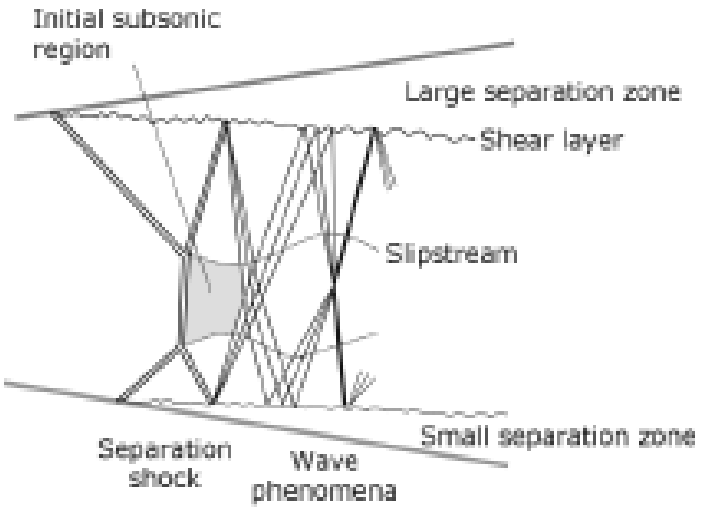
- **Steady expansion deflection computations for open- and closed-wake mode**
  - good wall pressure distribution
  - Base pressure predicted too low
  - Again earlier pressure rise

- **Comprehensive pressure variation**
  - Poor agreement with experiments
  - Trend of base pressure could be predicted well
  - Side wall separation is present. However, not responsile for the deviation in the base pressure





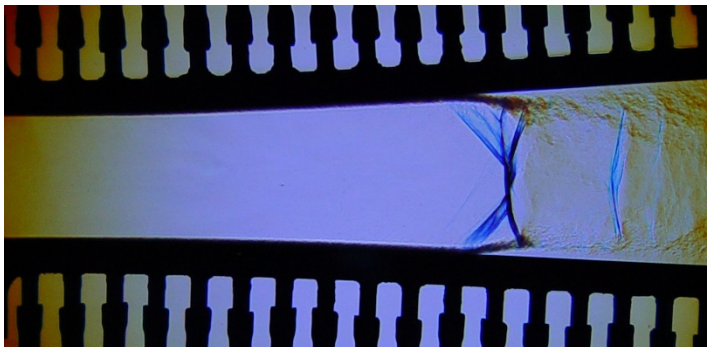
(a) Experimental nozzle geometry- far



Exerimental Setup

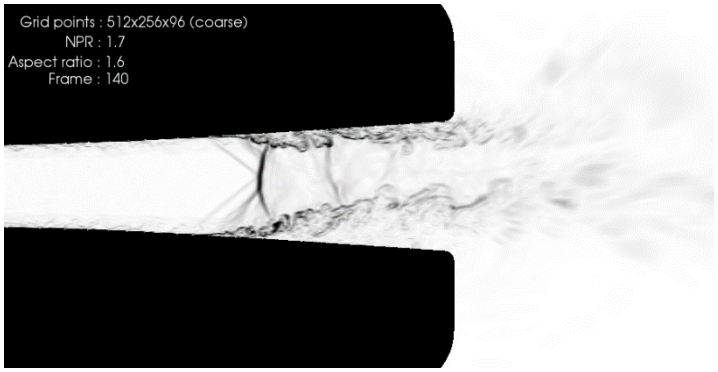
- Simplified planar nozzle geometry studied to identify sources (Papamoschou et.al.)
- Shape of nozzle (A_e/A_t=1.0 … 1.8) and Nozzle pressure ratio (NPR=1.2…2.4) can be changed
- Shock motion drives downstream instabilities and generates side loads
- Asymmetric separation with large separation zone on one side and smaller on the other
- Spontaneously oscillating shock pattern
- The mechanism of the instability is not fully understood from experiments



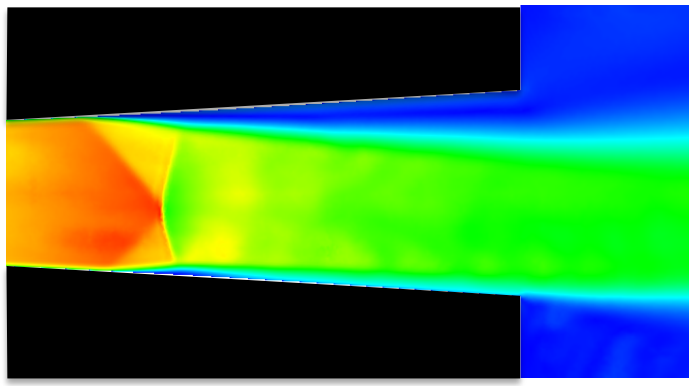


Experiment – Papamoschou & Zill

- Complex shock boundary layer interaction affects the dynamics of the flow.
- Low order methods (RANS) can't capture the unsteady dynamics properly
- LES captures the unsteady schock-turbulence interactions in a good approximation.

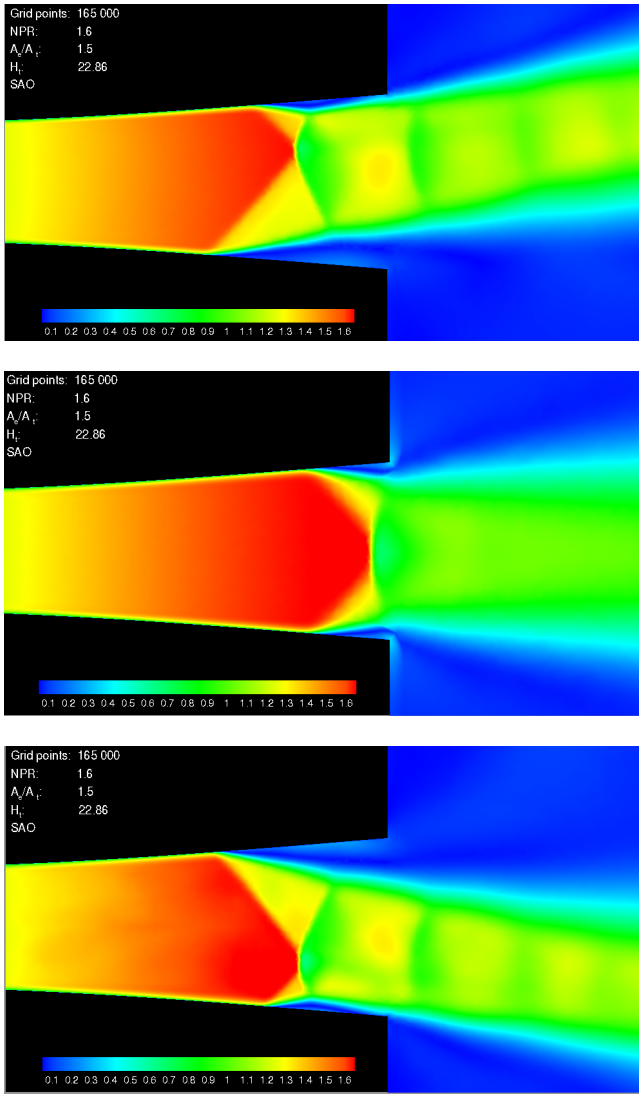


LES – LLNL Miranda Code



RANS – DLR TAU Code





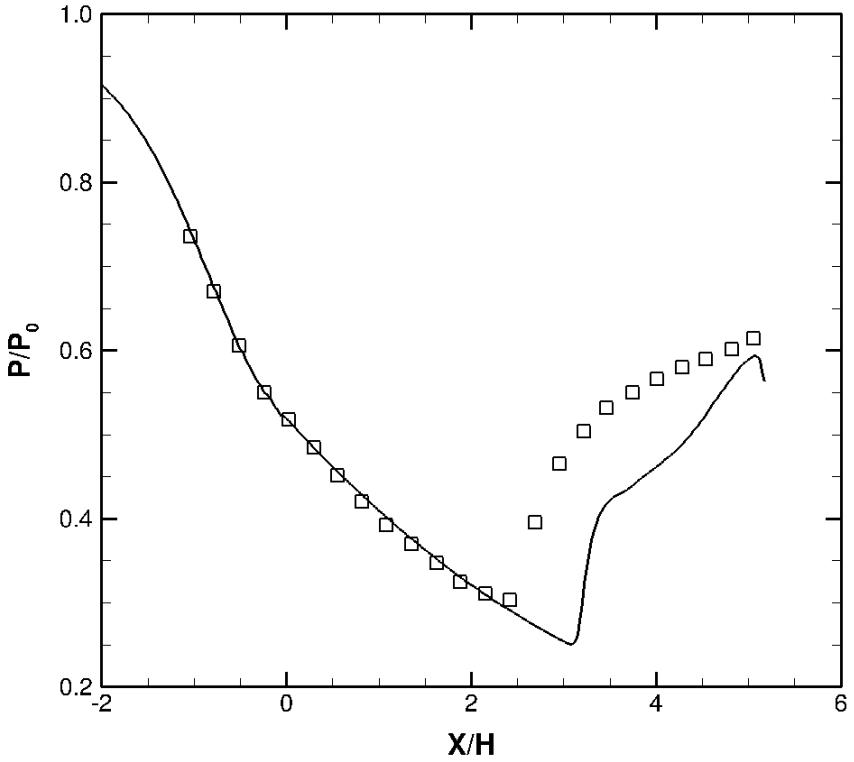
Reynolds Averaged Navier-Stokes (RANS)

- **Xiao & Tsai – Numerical Investigation of** Supersonic Nozzle Flow Separation (AIAA 2007)
  - 1.4 < NPR < 2.4 three different flow states
  - 1 symmetric and 2 asymmetric
  - Sides don't switch after steady state reached
  - No Difference between uRANS and RANS

- **Used flow solver – DLR TAU Code**
  - AUSMDV Upwind Second order MUSCL
  - Relaxation solver: Implicit Backward Euler
  - Linear Solver: LU-SGS
  - Res. Smoother: Upwind Implicit
  - Turb. Model: SAO – Spalart-Allmaras Original

A. Outlook

A.1 Large-Eddy and RANS simulation of flow in over-expanded rocket nozzles

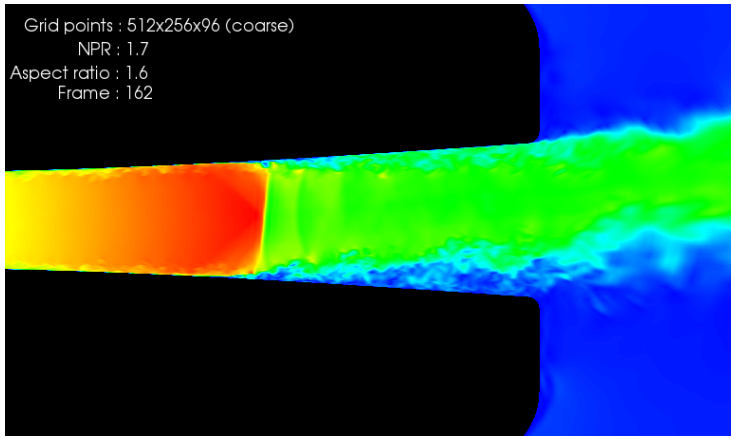


- Poor agreement of separation with experiment

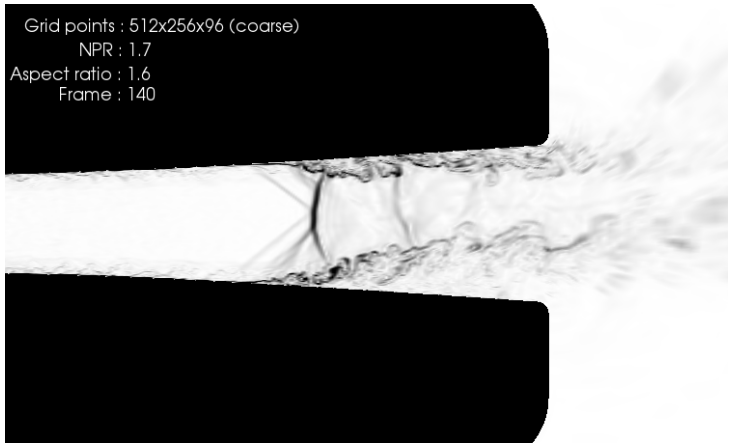
→ Improvement of separation position with local grid refinement

→ Different turbulence models have shown a more upstream separation (Menter SST, kω-Wilcox, RSM)

Large-Eddy Simulation (LES) – LLNL Miranda Code

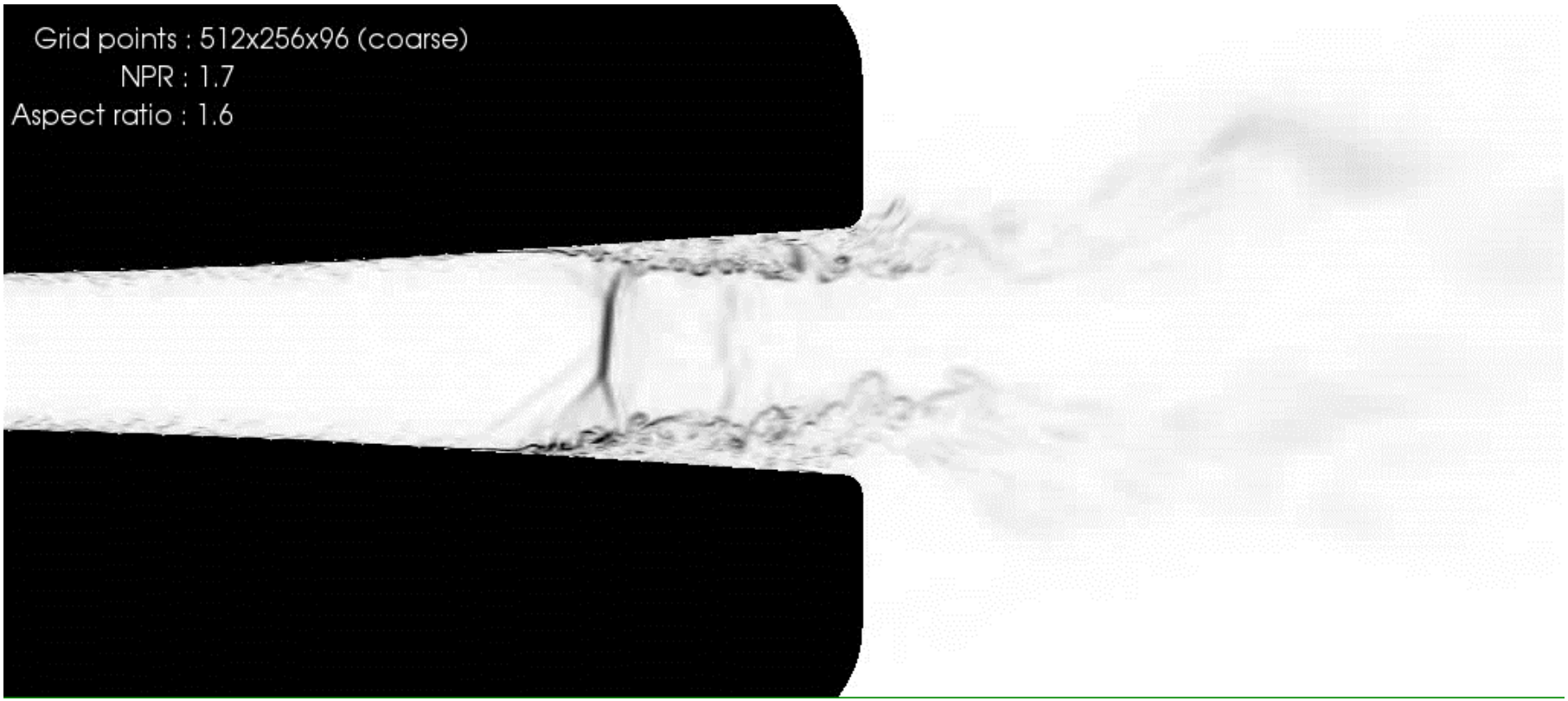


- 10^{th}-order compact central difference scheme
- Compressible Navier-Stokes
- 5 stage 4^{th} order Runge-Kutta scheme
- Implicit LES with artificial viscosity models
- Wall resolved with no-slip BC



- 512 x 256 x 96 (coarse)
- 768 x 384 x 128 (medium)

Large-Eddy Simulation (LES) – LLNL Miranda Code



Future Work

- Additional turbulence models with RANS
- Implementing side walls to the simulation
- Increasing the Reynolds number (wall modeled LES)
  → currently ~ 1/4th of experimental value (4.2×10^5 … 6.4×10^5)
  → geometric ratio of boundary layer thickness to throat increased by factor 2
- Rotational-symmetric nozzle instead of planar nozzle
- Simulations with more realistic nozzle area ratios







4. The Expansion-Deflection Nozzle (ED)

4.3 Cross section and flow field – open wake mode

