Comparison of steady and unsteady RANS CFD simulation of a supersonic ORC turbine

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Context

- ORC systems need high efficiency and cost-effective expanders
- **Multi-stage axial turbines** are the most commonly used solution for applications above 1 MW
- For high temperature applications ($T_{HS} > 250/300°C$), highly loaded **transonic to supersonic stages** are used to keep their number low
- Accurate design and performance estimation through CFD must be used to ensure high turbine efficiency

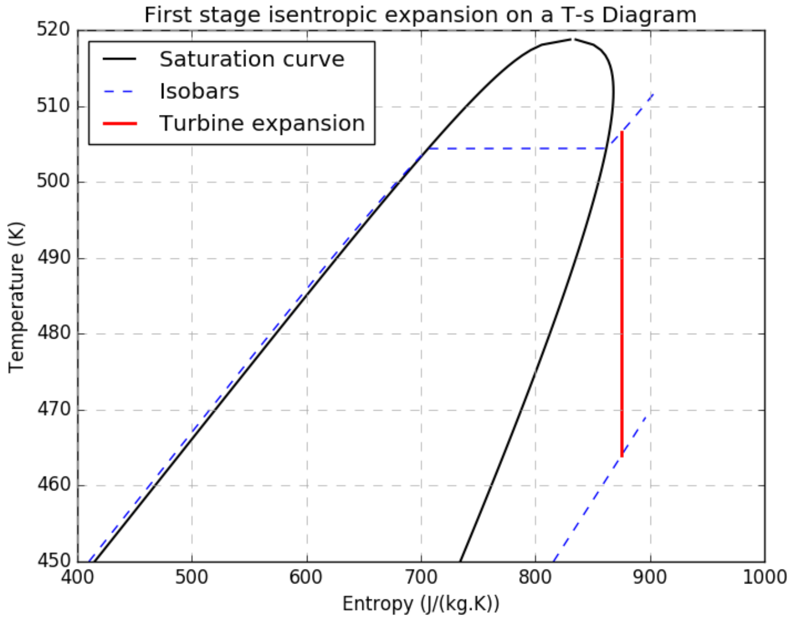
Objective

- Design of a highly loaded turbine stage
- Simulations using **unsteady** Reynolds Averaged Navier-Stokes (RANS) calculations to capture transient nature of the flow inside of an axial turbine stage
- Analyse **flow structure** including **shock interactions** and **blade loading**
- **Performance** assessment (entropy creation and isentropic efficiency)
- **Comparison with steady state** mixing plane RANS simulations

Turbine Characteristics

- Working fluid: siloxane **MM** (hexamethyldisiloxane)
- **3-stage 2.5 MW axial turbine** running at 3000 rpm
- 85 overall pressure ratio
- Inlet total temperature: 233°C
- Inlet total pressure: 14.5 bar

In this work we focus on the **first stage of the turbine**



T-s Diagram

First Stage Characteristics

- Impulse stage (low reaction degree)
- Converging diverging nozzle
- Number of blades determined using Zweifel optimal loading coefficient

Parameters	Value	Parameters	Value
Pressure ratio	7.5	Blade height	20 mm
Specific speed	0.2	Rotor inlet Mach number	0.8
Specific Diameter	6.2	Rotor outlet Mach number	1.2
Nozzle outlet **Mach number**	**1.84**	Rotor inlet blade angle	62°
Nozzle outlet blade angle	76°	Rotor outlet blade angle	64°
Nozzle blade number	47	Rotor blade number	142

Changed to 141 to reduce computational domain

Dense gas behavior

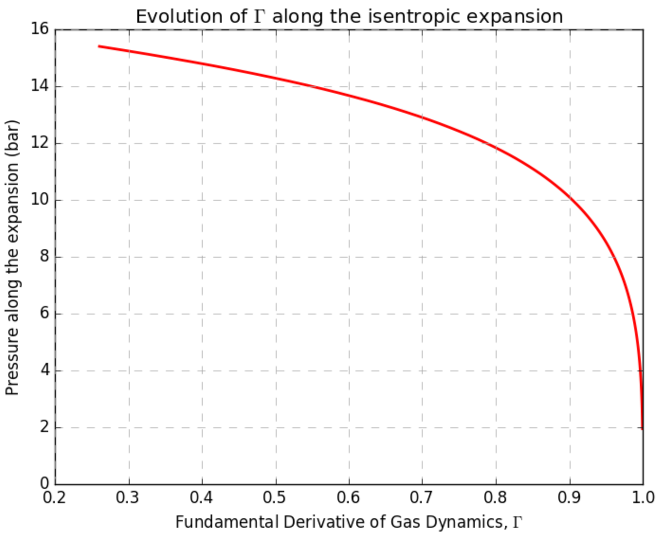
- MM properties from multi-parameter Equation Of State (EOS) based on Helmoltz free energy [Colonna et al, 2006]

- Fundamental derivative of gas dynamics [Thompson, 1971]:

$$\Gamma = 1 + \frac{\rho}{a}\left(\frac{\partial a}{\partial \rho}\right)_s$$

- $\Gamma \in [0.25, 1.0]$ along first stage expansion
  - Classical behavior when $\Gamma > 1.0$
  - Non classical behavior $\Gamma < 1.0$

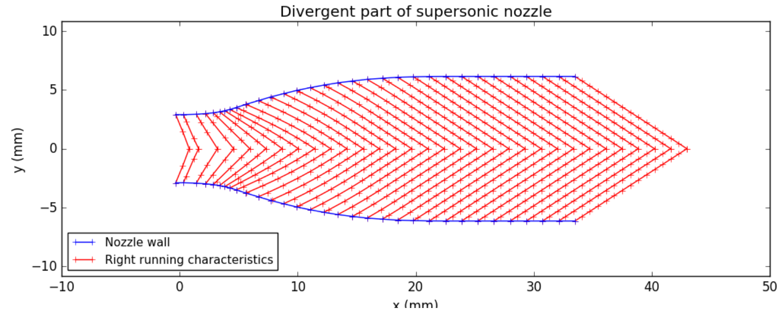
- Dense gas effects expected



Γ evolution along expansion

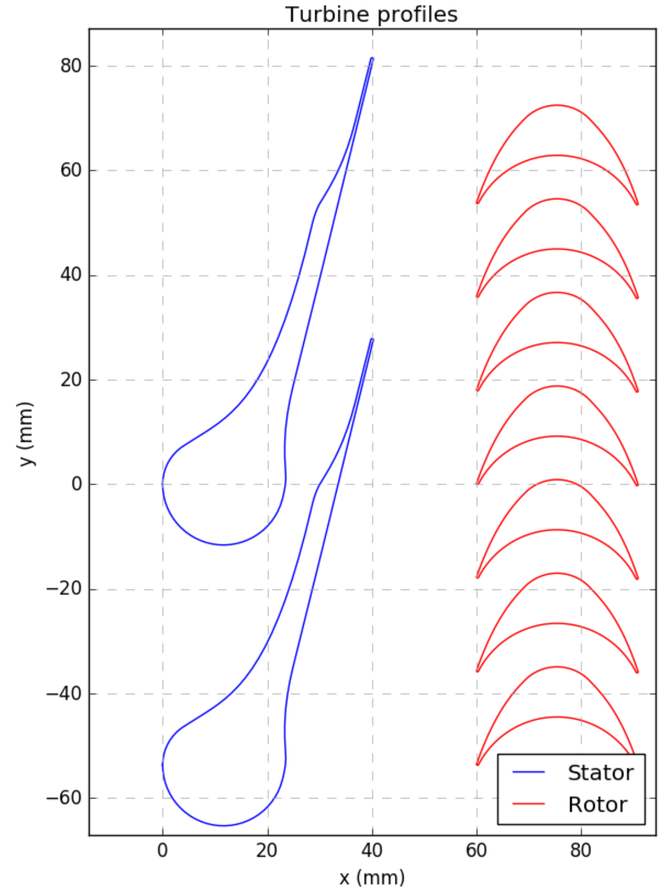
Blade design

- **Nozzle divergent** part designed using Method Of Characteristics (**MOC**) extended to real gases



- **Nozzle convergent** part designed using simple geometrical shapes

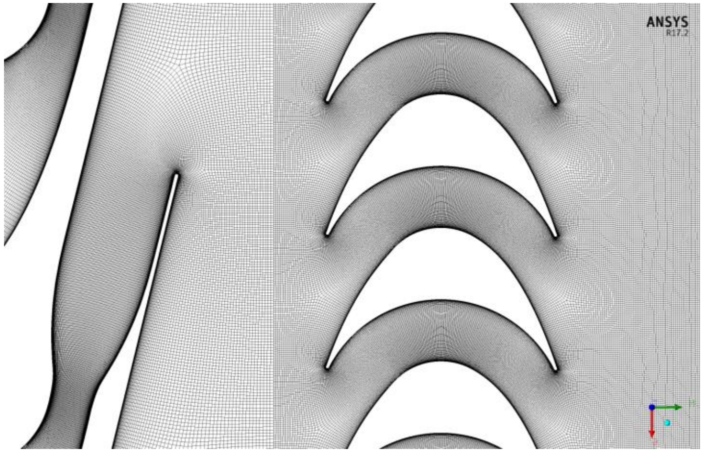
- **Rotor blades** designed using
  - Circular arc for pressure side
  - Circular arc and splines for suction side
  - Ellipses for leading and trailing edges



First Stage Geometry

CFD simulation setup

- Commercial software: **ANSYS CFX 17.2**
- **Unsteady RANS 2-D, k-ω SST** for turbulence closure
- Real gas properties: look up tables generated from **NIST REFPROP**
- Numerical schemes
  - Advection scheme: implicit 2nd order bounded scheme
  - Turbulence scheme: implicit 2nd order bounded scheme
  - Transient scheme: implicit second order Euler (60 steps per period)
- Boundary conditions:
  - Total inlet pressure and temperature
  - Static outlet pressure
  - No slip blade wall
- Mesh:
  - 350,000 elements
  - Structured grid
  - **y+~1** at walls
  - Grid independence study



Simulation mesh close up

Flow structure

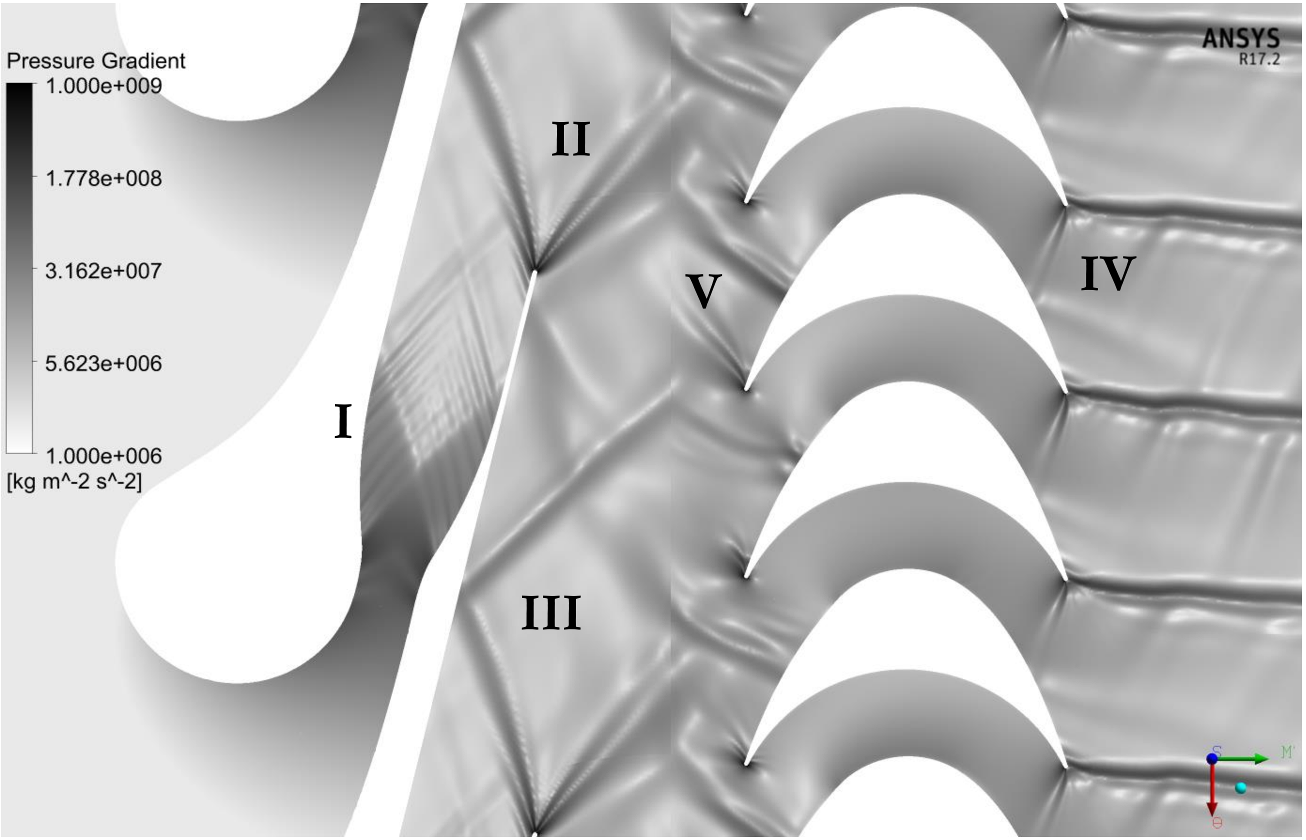
I: Series of weak oblique shocks

II: Fish tail shock

III: Reflexion

IV: Fish tail shock Reflexion

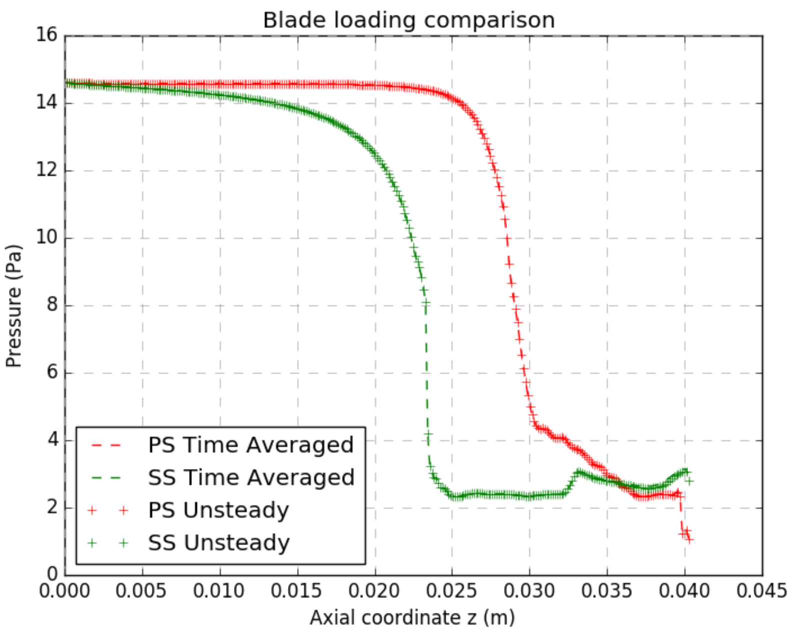
V: Bow shock



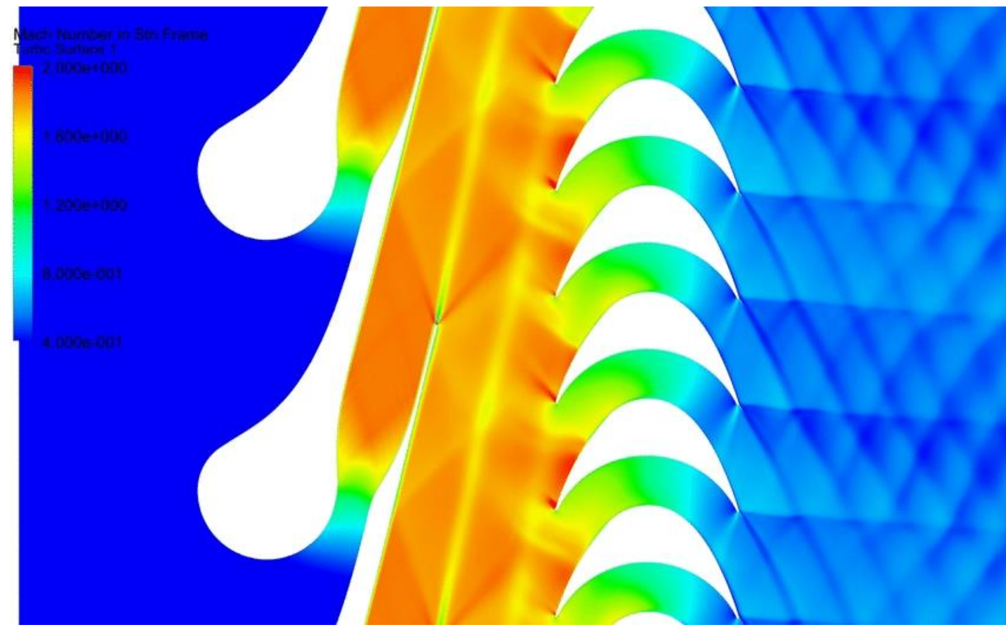
Pressure gradient

Nozzle blade loading

- The flow acceleration in the nozzle is essentially stationary
- Fish tail shock impingement thickens boundary layer at the suction side
- Small fluctuation near the trailing where bow shock impinges
- Second boundary layer thickening at this impingement



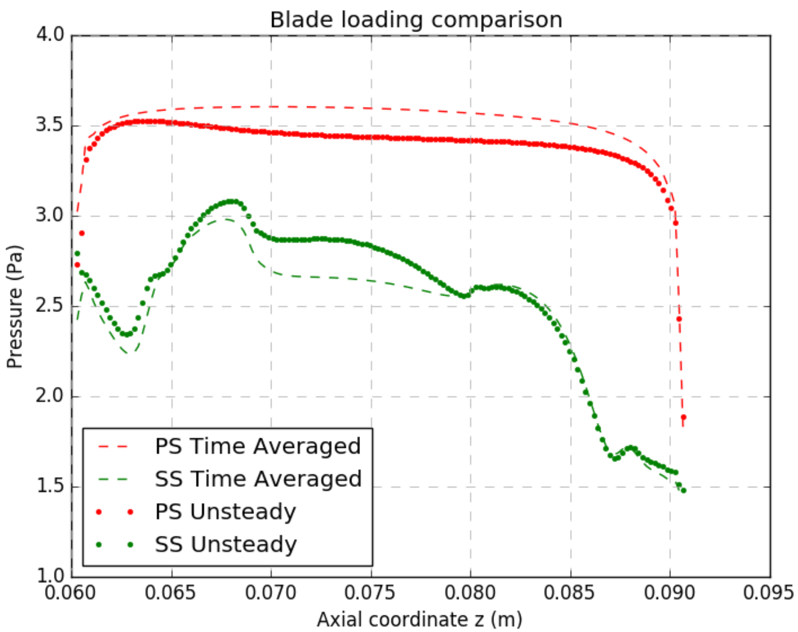
Stator blade loading



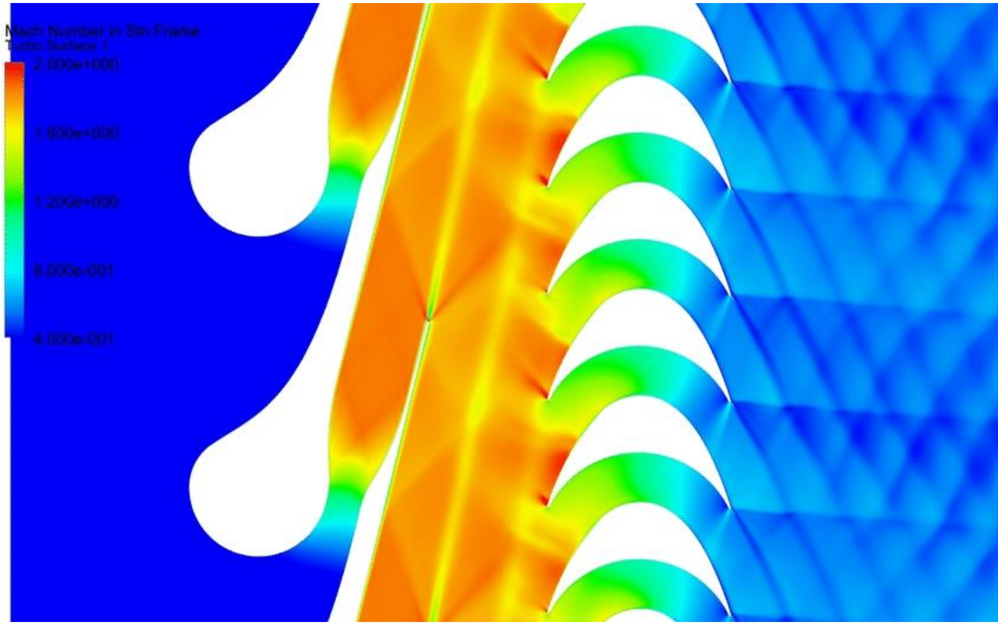
Mach number in stationary frame

Rotor blade loading

- Front part of the rotor blade sees important blade loading fluctuations due to bow shock interacting with shocks and wake coming from the nozzle row.
- Rear part has a more steady behavior



Rotor blade loading

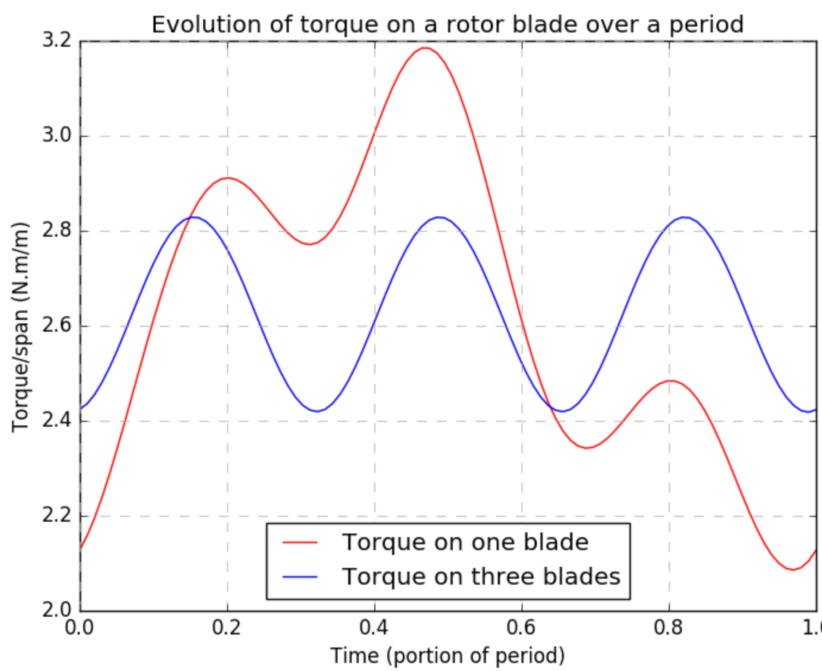


Mach number in stationary frame

Rotor blade loading

- The torque on one blade varies by more than 40% and the average torque on the three rotor blades of the domain varies by about 20%

Rotor blade loading



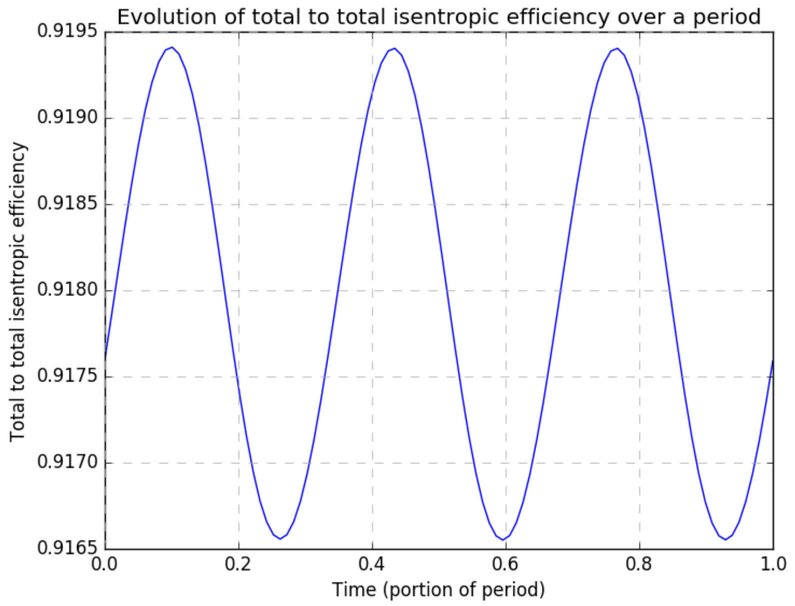
Rotor torque evolution

Losses

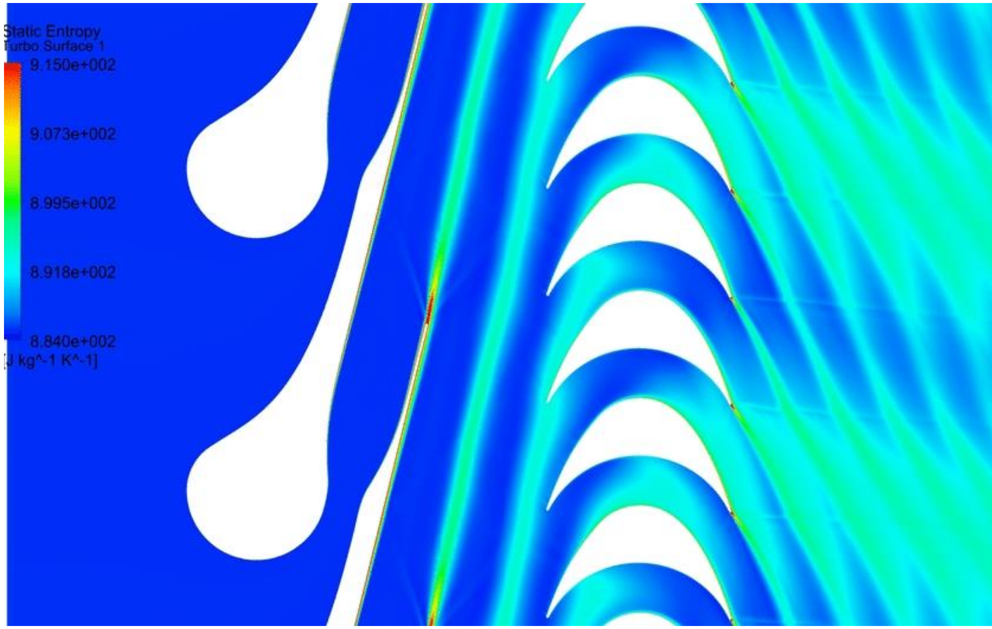
- Entropy creation dominated by nozzle turbulent wake advected through the rotor blade row
- Rotor turbulent wake
- Small contribution of shocks to entropy creation

$$\eta_{tt} = \frac{H_{in} - H_{out}}{H_{in} - H_{out,isentropic}}$$

Total to total isentropic efficiency



Isentropic efficiency time evolution



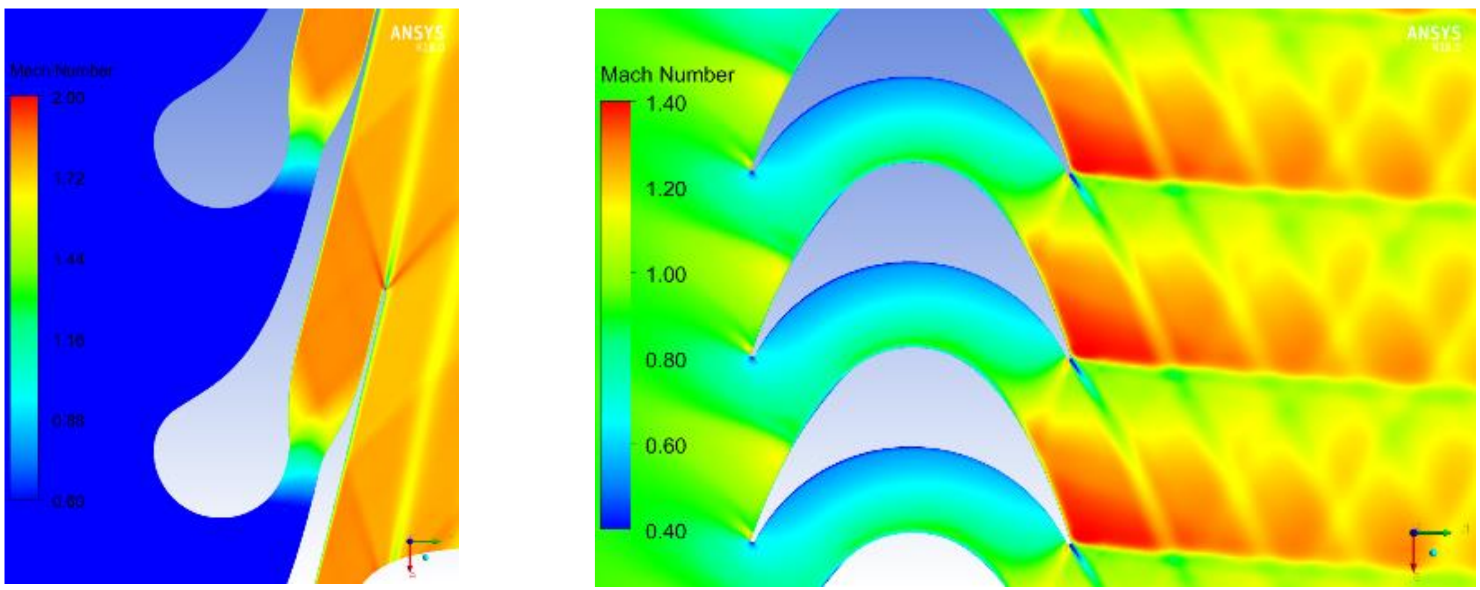
Entropy field

Comparison with steady results

Setup:

- Stator/rotor interface: mixing plane
- Same boundary conditions
- Same advection and turbulence schemes

Results:

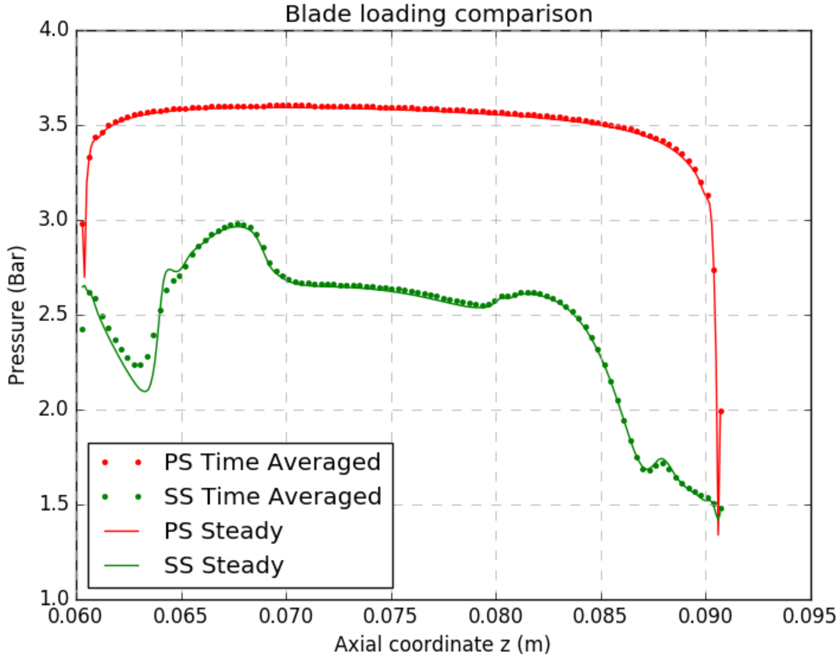


Mach number fields

Comparison with steady results

- Nozzle flows are very similar
- Small differences in front part of the rotor blade where stator-rotor interaction is important

Quantities	Steady	Unsteady
Stator total pressure loss coefficient	0.1000	0.1022
Rotor blade torque (N.m/m)	2.6299	2.6255
Total to total isentropic efficiency	0.9193	0.9179



Rotor blade loading

Conclusion and Perspectives

Conclusions

- Expected flow structure
- High variation of rotor load but lower than in similar work [Rinaldi, 2015]
  - → Larger gap (0.5 chord vs 0.25 chord)
  - → Lower Mach number (1.8 vs 2.8)
- Good prediction with mixing plane steady simulations

Perspectives

- Reduced stator-rotor gap would increase stator-rotor interaction effects
- 3D unsteady simulations:
  - → Low h/D ratio for the first stage
  - → Important secondary flow contribution expected
- Comparison with time/harmonic transformation methods available in ANSYS CFX
- Simulation of transonic and higher reaction degree stages

Thank you for your attention