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Aerodynamics of Centrifugal Turbine Cascades

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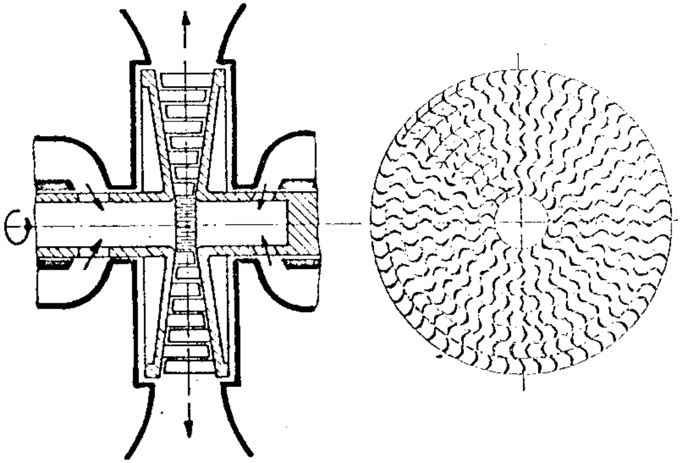
Unconventional character of ORC turbines

- High volumetric expansion ratios → large passage area ratio
- Small enthalpy drops → low number of stages (one-two)
- Organic fluid complexity → low speed of sound

→ highly supersonic axial or centripetal turbines

Interesting alternative: **multistage centrifugal turbine (Exergy configuration)**

- Multistage arrangement in compact configuration
- Intrinsic streamwise increase of cross section
- Novel blade design features for centrifugal set-up



Outline

- Preliminary design of a multistage centrifugal turbine
- Aerodynamic design of centrifugal turbine blades
- Three-dimensional aerodynamics of centrifugal stators
- Inertial effects in centrifugal rotors

Preliminary design of a siloxane MDM turbine

Pini et al., JEGTP 2013 – ORC Special Issue

Target conditions

1. Power: 1 MW
2. Flow rate: 22 kg/s
3. Expansion ratio: 60

Stage design data

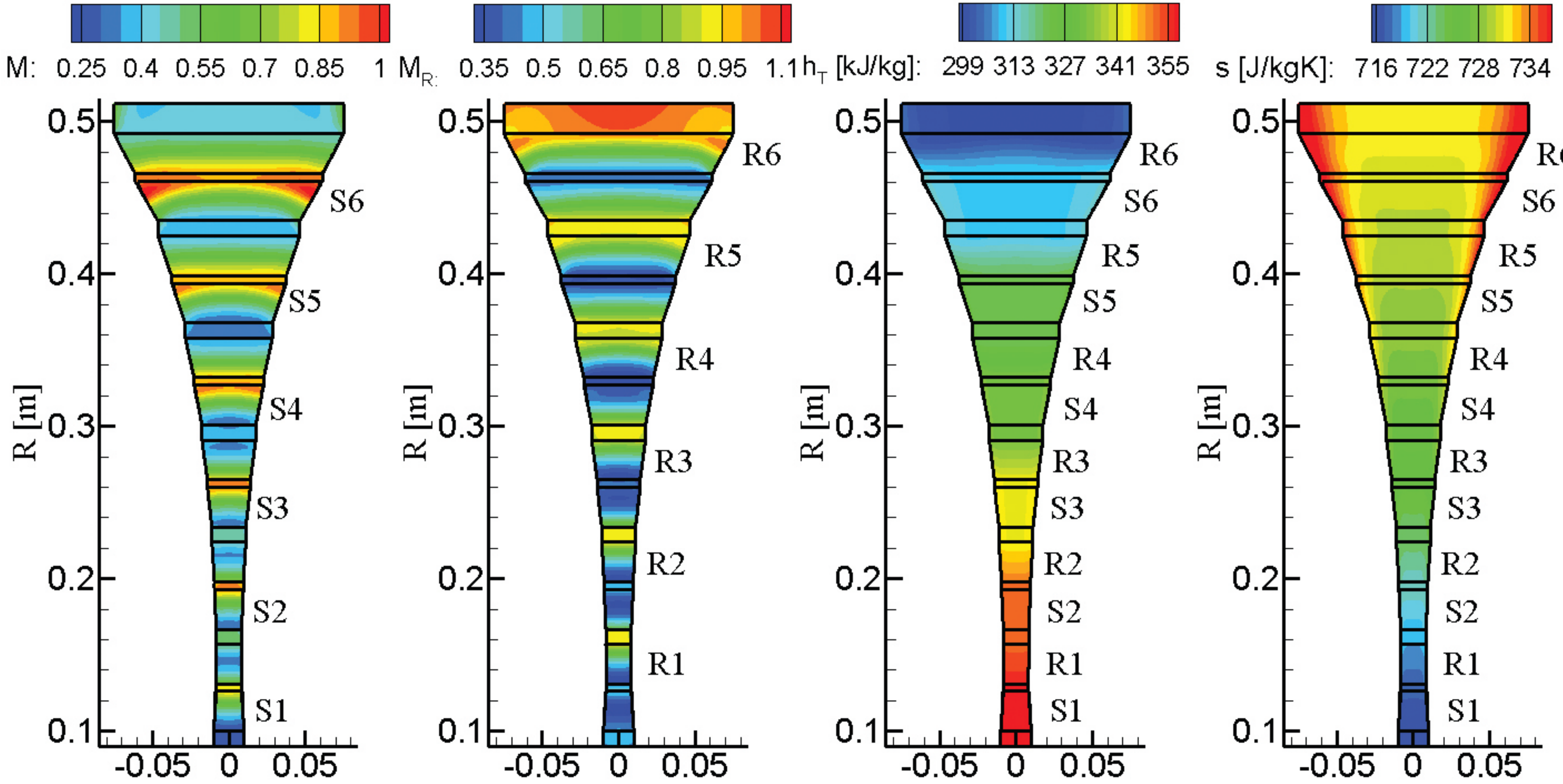
1. M_{MAX} =1.0
2. χ = 0.5
3. $Flaring_{MAX}$ =30°

Results

1. N stages = 6
2. D_{OUT} = 1 m
3. η_{TT} = 87 %

Throughflow results confirm expectations:

- ✓ Transonic machine
- ✓ No chocking in design
- ✓ High performance



Relevance for aerodynamic study

Preliminary design suggests relevant features of centrifugal turbines

but

performance estimates based on correlations

and

lack of knowledge in open literature about centrifugal cascades

Investigations on aerodynamics of centrifugal turbine cascades required

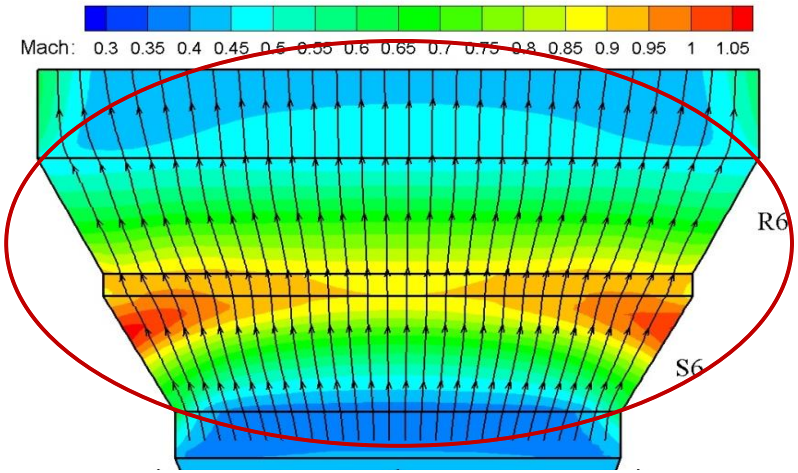
to

provide design indications

investigate specific flow features

evaluate the reliability of classical correlations (for axial machines)

Stator and **rotor** of the **sixth stage** computed in stand-alone configuration



- Fully-3D / quasi-3D steady flow model
- Hexahedral grids with 1.5 / 0.1 Mcells
- Solver: Finite Volume ANSYS-CFX, with:
  - . HR methods for inviscid fluxes
  - . centred scheme for diffusive terms
- Turbulence model: k-ω SST with near-wall boundary layer solution (wall $y^+ \sim 0.3$)
- Boundary conditions
  - . Total quantities, flow angles and turbulence properties imposed at the inlet
  - . Static pressure assigned at the exit (iterations due to the vaneless diffusion)
- CFD model validated against experiments (Persico et al., 2012, ASME J. Turbomach.)

Methodology
Fluid thermodynamic model

- Siloxane MDM thermo-physical properties - estimated using FluidProp© :

$$Z_{IN} = 0.986 \qquad Z_{OUT} = 0.995$$

- Preliminary trials performed with Look-Up-Table approach

- Tests performed with PIG model, calibrated on mean properties.

- Pressure field comparison shows negligible real gas effects

→ **PIG** model used for the calculations

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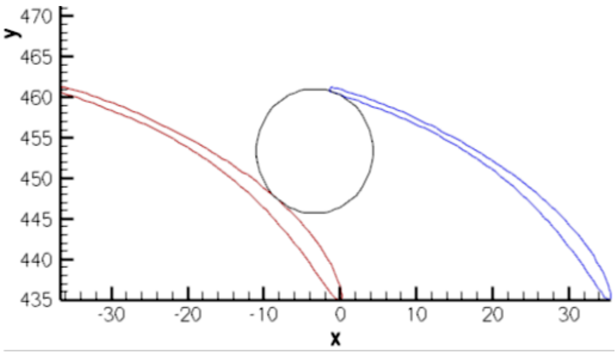
Construction of blade profile

Blade row	α_{IN} / β_{IN} [°]	α_{OUT} / β_{OUT} [°]	M_{OUT}	$\sigma_b = b/s$ (zweifel)
Sixth stator	25°	66.2	0.93	0.75
Sixth rotor	-36°	-66.2	0.99	0.65

- No radial equilibrium in spanwise direction → spanwise design not required
- Blade angle definition:
  . null incidence angle imposed in design condition
  . deviation estimated via Ainley-Mathieson corr:
  → Gauging $o/s = f(\alpha_{OUT}$ (or $\beta_{OUT}) - dev)$



- Blade construction approach:
  . mean line assigned
  . combined with thickness to define SS and PS

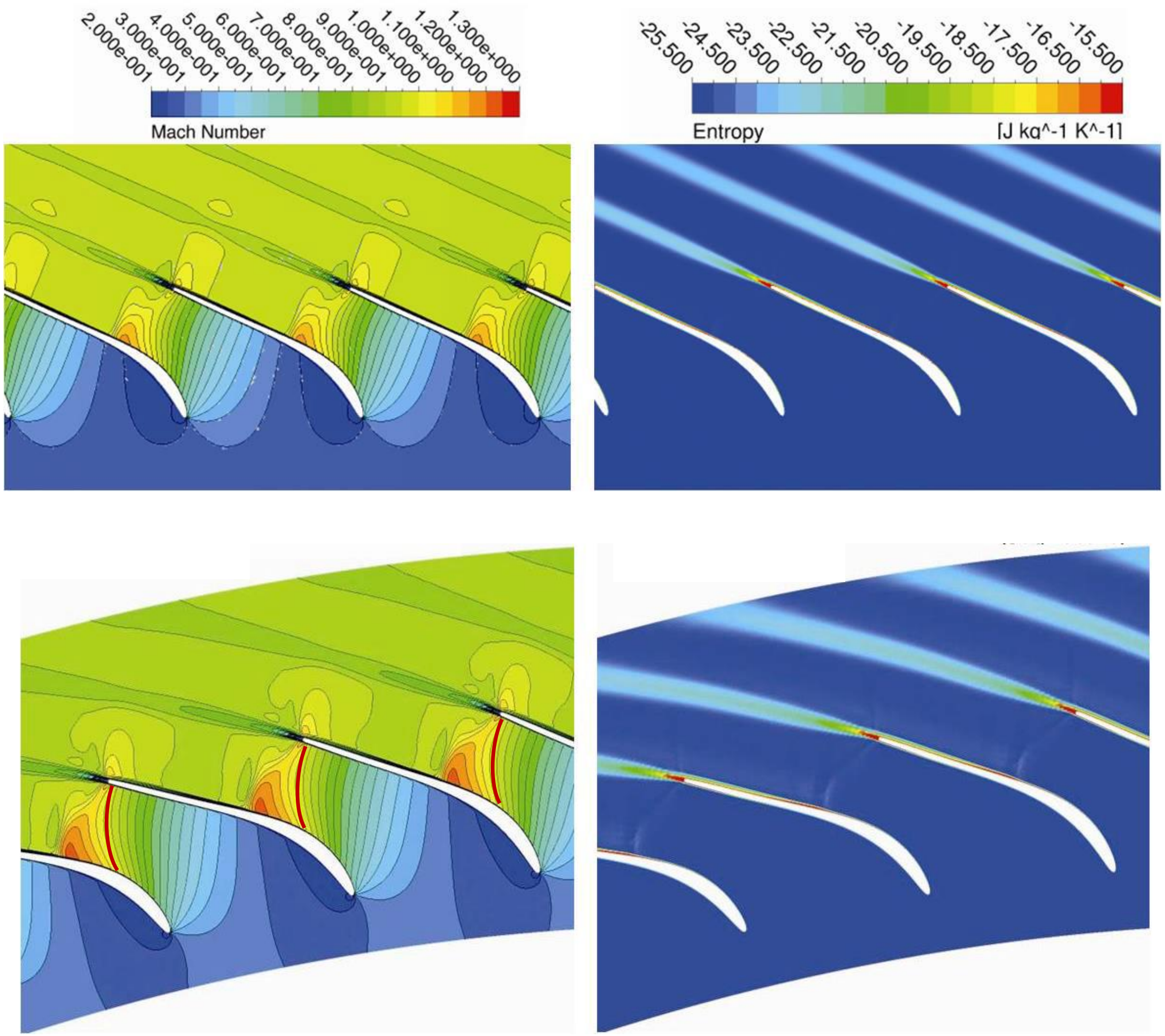
- Conformal mapping of the blade sides to conserve the geometric blade angles (not flow!)

$$r_p = r_{in}\left(e^{\frac{q}{b}(x_p - x_{ref})}\right)$$

$$\theta_p = \frac{q}{b_{ax}}(y_p - y_{ref})$$

Front-loaded vs aft-loaded profiles

Front loaded blade aerodynamics

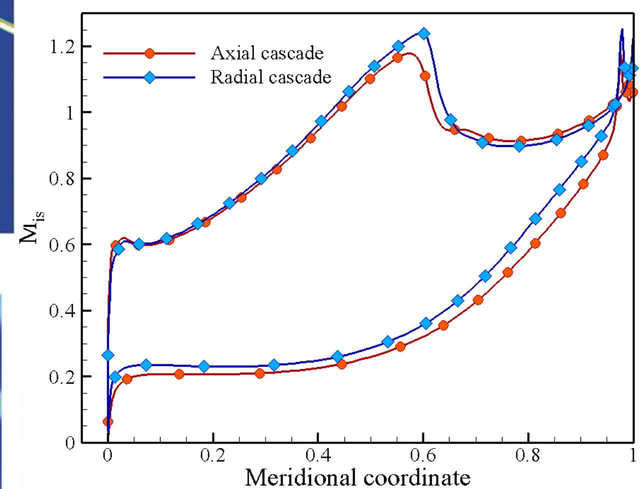


Smooth flow in axial case

Sonic throat **within** the bladed channel in centrifugal case

→ Straight rear part divergent in centrifugal case!

Chocked-flow, stronger shock

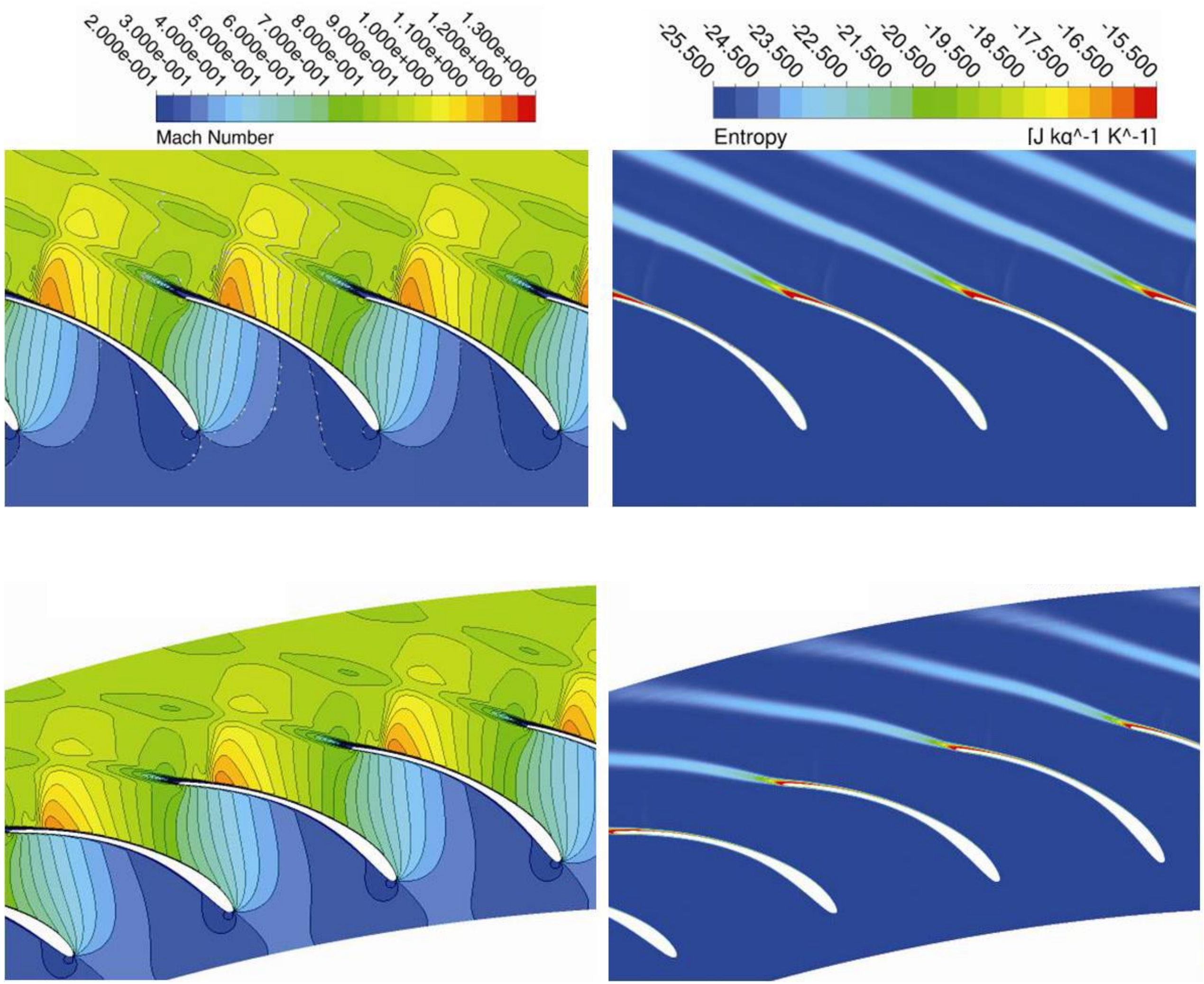


→ Higher losses

Configuration	δ	ζ	ζ_{mix}
Correlations	0.43°	2.74%	2.74%
Axial	0.45°	3.35%	3.84%
Centrifugal	0.54°	4.96%	4.99%

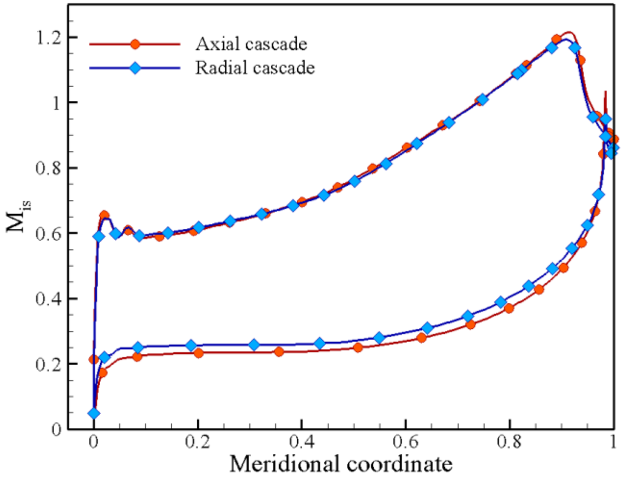
Front-loaded vs aft-loaded profiles

Aft-loaded profile: Elliptic Arc Mean Line blade



Smooth flow in both cases

Almost identical expansion process in axial/radial config.



Same strength of SS shock

→ Similar performance

→ Reliability of A-M dev corr

Configuration	δ	ζ	ζ_{mix}
Correlations	-1.9°	2.74%	2.74%
Axial	-1.7°	3.53%	4.01%
Centrifugal	-1.9°	3.00%	3.27%

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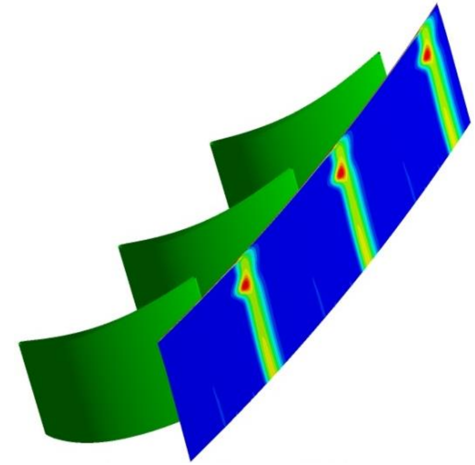
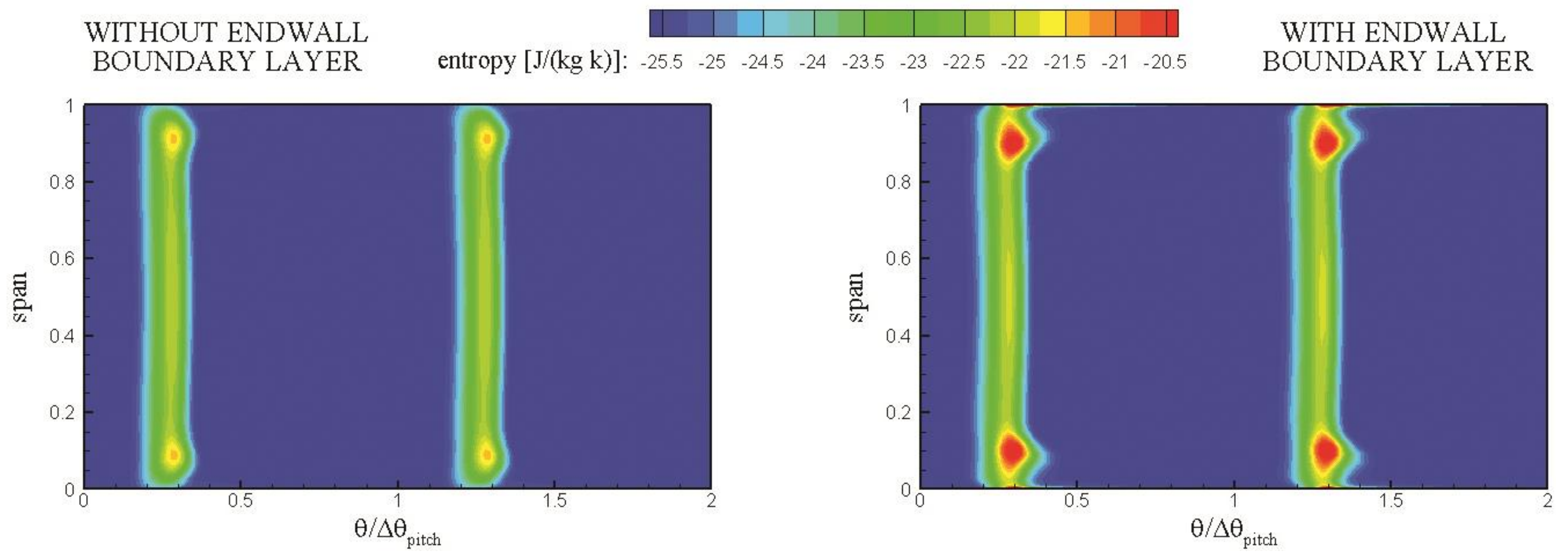
EAML-profile cascade
Three-dimensional flow configuration



Endwall boundary layer treatment:

(a) Endwall slip condition → flaring effects isolated

(b) Endwall No-slip condition → secondary flows included



(a): wake endwall gradient due to flaring → spanwise variation of blade loading

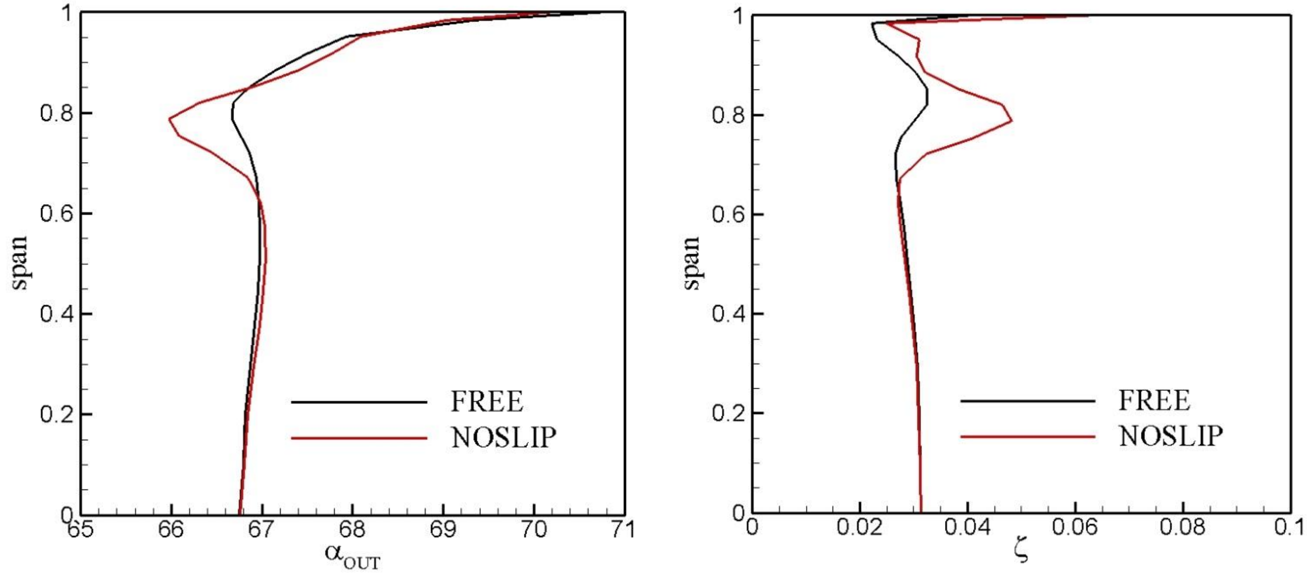
(b): distinct loss cores due to secondary vortices → no rad. eq., spanwise symmetry

EAML-profile cascade
Spanwise profiles and performance

- Spanwise gradients without endwall BL due to flaring

→ meridional velocity ↓, flow angle ↑ (1° in mean flow angle)

- Larger effects in case of secondary vortices: over/under-turning, loss peaks



Cascade	C-C corr (3D)	CFD-quasi 3D	CFD-3D-slip	CFD-3D-noslip
ζ_{mix}	7.3	3.27	3.7	4.03

computed overall loss coefficient 40% smaller than correlation prediction

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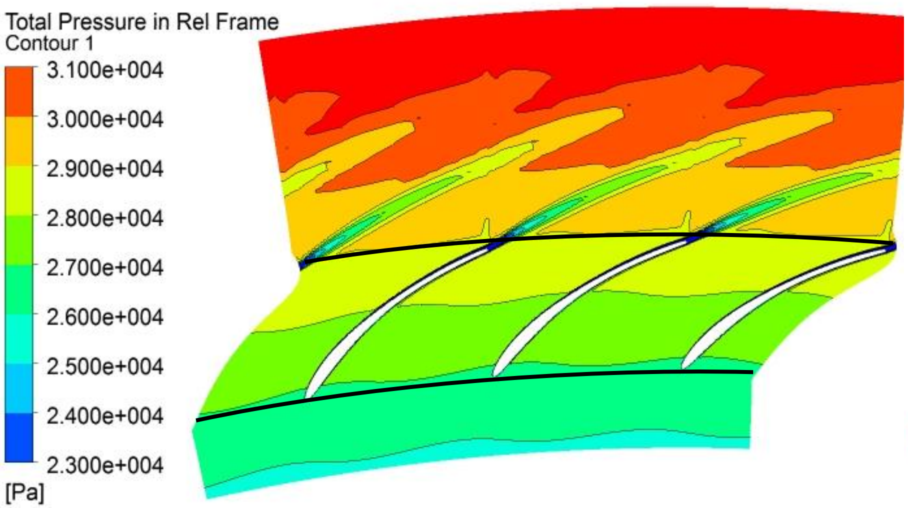
Inertial effects in rotating centrifugal cascades

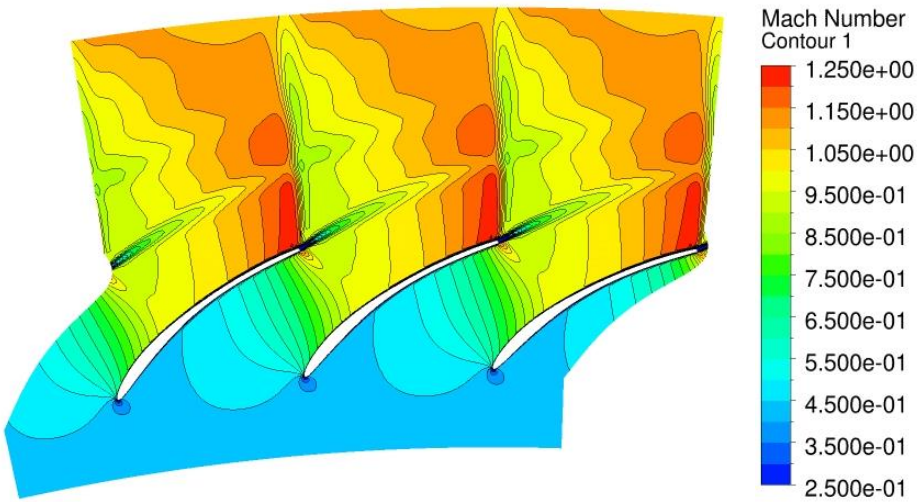
Apparent forces features

Coriolis and centrifugal forces → impact on profile aerodynamic design?

Centrifugal force → T_{TR}, P_{TR}, M_R ↑ in outward direction → strong TE shock

Coriolis force → slip effect on flow angle → more tangential flow expected



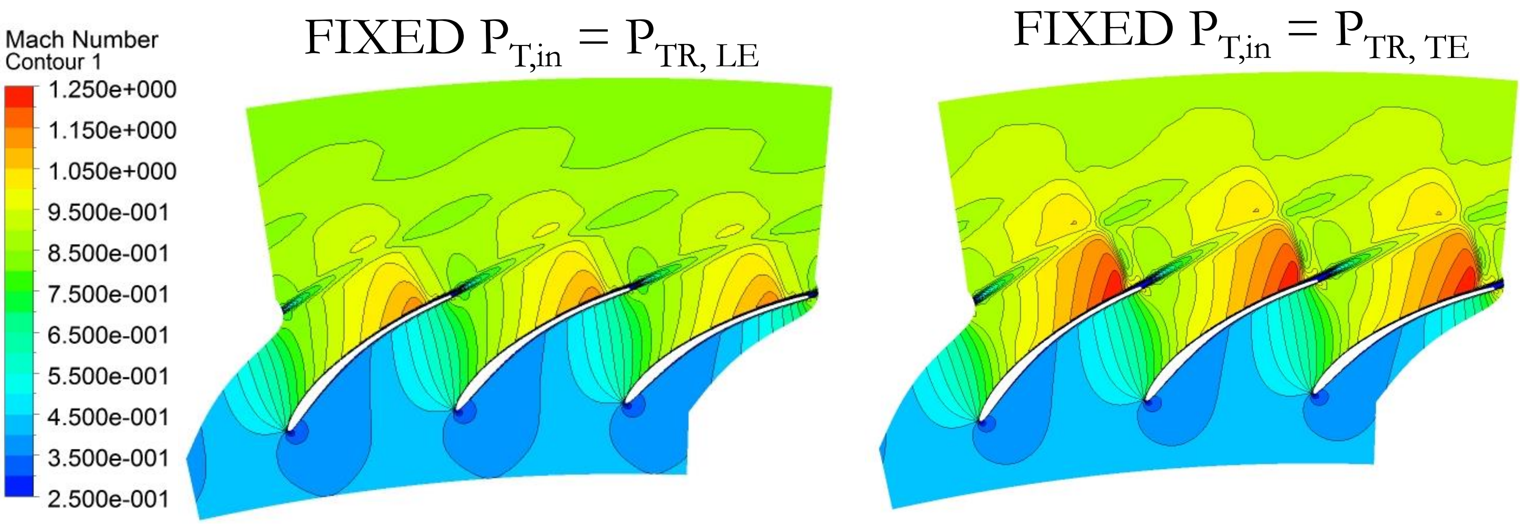


Fixed-rotor calculations assigning relative quantities to highligh inertial effects

Not univocal choice of inlet relative total quantities → both LE & TE considered

Inertial effects in rotating centrifugal cascades

Impact on aerodynamics & performance



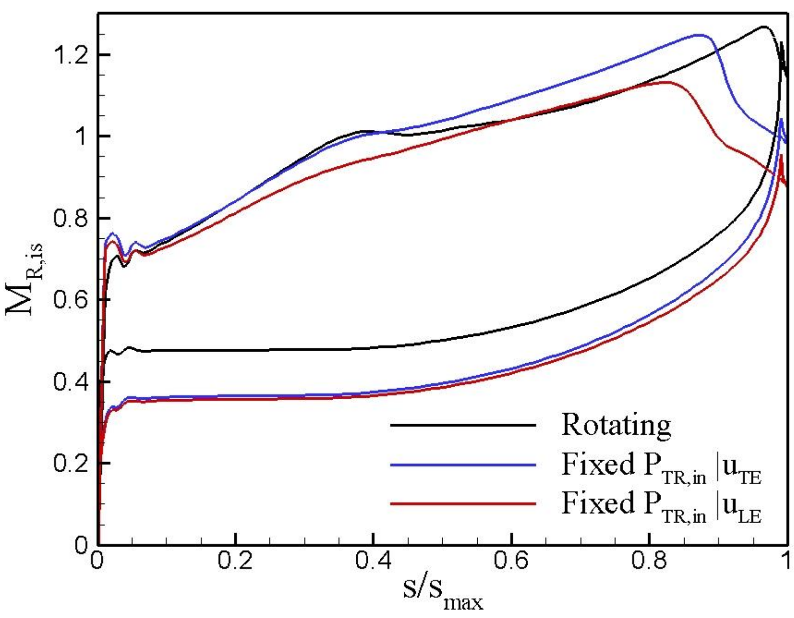
$P_{T,in} = P_{TR,\,LE}$ → no match in M_{OUT}, no shocks

$P_{T,in} = P_{TR,\,TE}$ → match in M_{OUT}, different shock

→ No way to reproduce pressure distribution of rotating blade rows with stationary experiments

More tangential flow due to (weak) Coriolis effect

Case	α_{OUT}	M_{OUT}	ζ_{mix}
Rotating	-67.6°	0.985	4.85%
$FixedRT_{IN}$	-67.1°	0.920	2.86%
$FixedRT_{OUT}$	-66.7°	0.989	3.68%



Conclusions

- Preliminary design **suggests** potential of centrifugal turbine architecture
- Aerodynamic study with high-fidelity CFD **assesses** turbine stage performance
- **Aft-loaded** profiles (such as **EAML**) outperform front loaded ones
- Three dimensional effects are relevant in case of large flaring
- Centrifugal force determines the aerodynamics of centrifugal rotor blade rows
  - → stator blade design criteria not entirely extendable to rotor blades
  - → stationary experiments of limited validity of rotor blade profiles

Loss correlations overestimate stage losses in preliminary design
→ last stage efficiency rises from 91.7% (preliminary) to 92.3% (H-F CFD)

Further step: to apply the design procedure to the first stages
→ to test the design strategy for higher radial effects
→ to evaluate the improvement in overall turbine efficiency