Associazione Termotecnica Italiana

AIDIC

FIL ROUGE 2026

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La modellazione fluidodinamica al servizio della progettazione: sviluppi recenti

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Con il contributo di

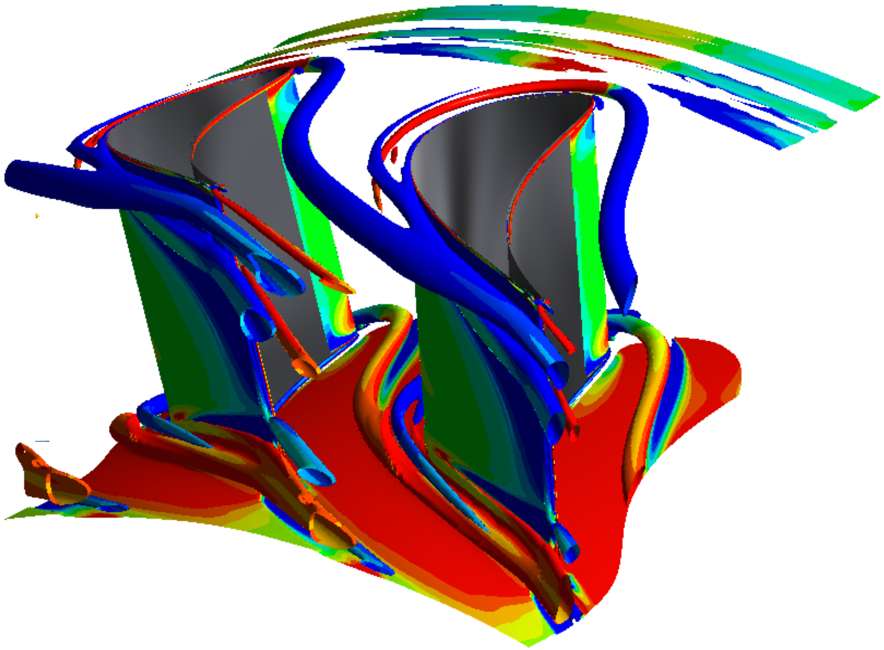
KSB

MASOL Continental Biofuel

Complexity of turbomachinery flows

✓ Turbomachinery aerodynamics combines internal and external flows

- blade pressure distribution
- blade boundary layer development
- wake shed by the trailing edge
- flow deflection
- endwall boundary layer development
- secondary and leakage flowswalls

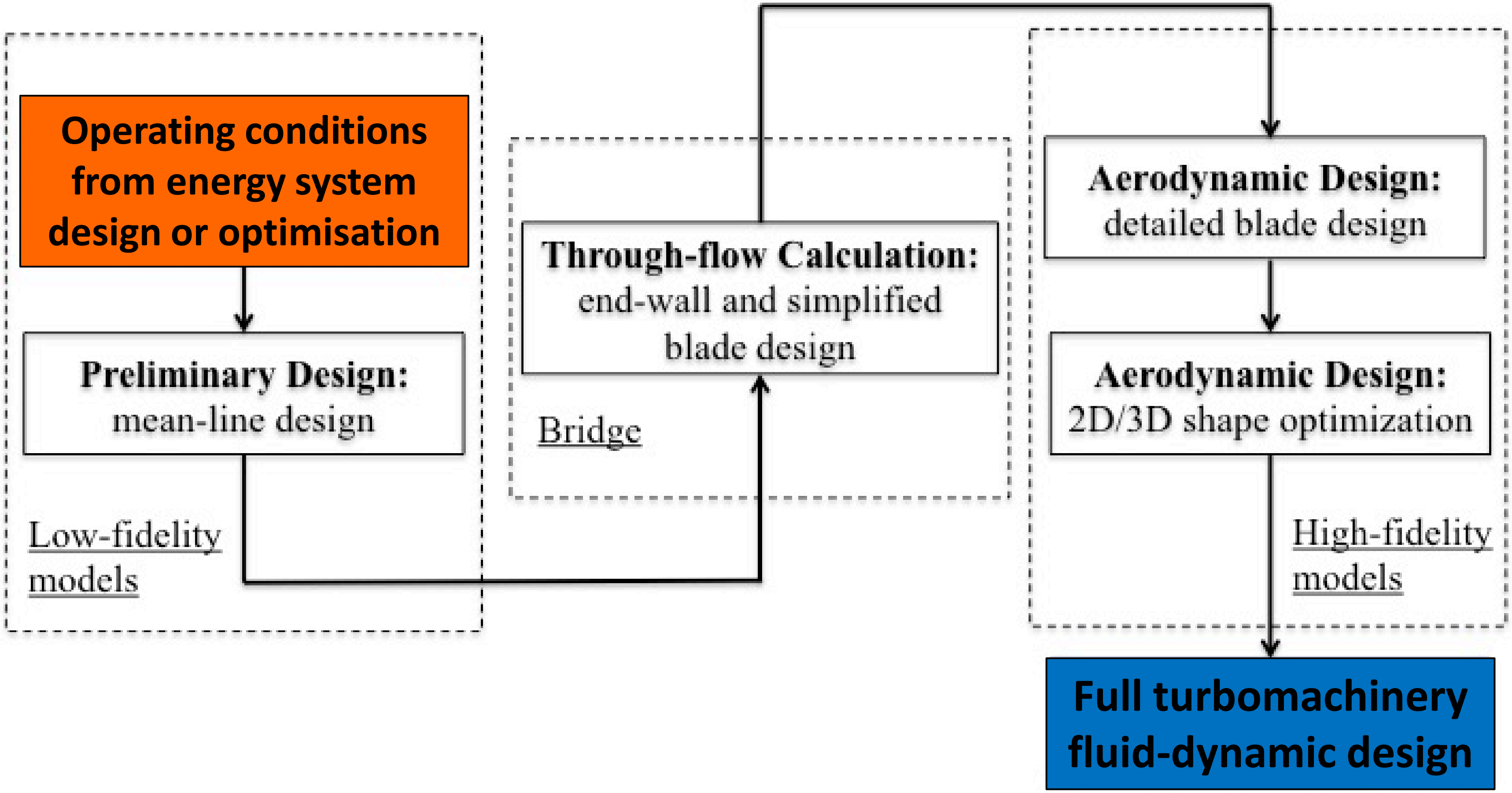


✓ Transonic and supersonic flow regime

- chocking, area-velocity relations, normal shocks
- oblique shocks, post-expansion

Several modeling techniques can be conceived for turbomachinery flows featuring different levels of complexity and fidelity

Turbomachinery design path



Outline

1. Mean-line model for flow-path design and analysis of multi-stage machines
2. Throughflow model for spanwise design of turbomachinery blades
3. High-fidelity modeling for analysis of 3D, unsteady turbomachinery flows
4. High-fidelity design of turbomachinery by AI-based shape-optimization
5. Modeling challenges of novel turbomachinery

Mean-line model

Mean-line model

<u>Basic tool for preliminary design</u>:

→ Stage number, stage style, angular speed, etc..

→ Velocity triangles at midspan, blade angles, blade span

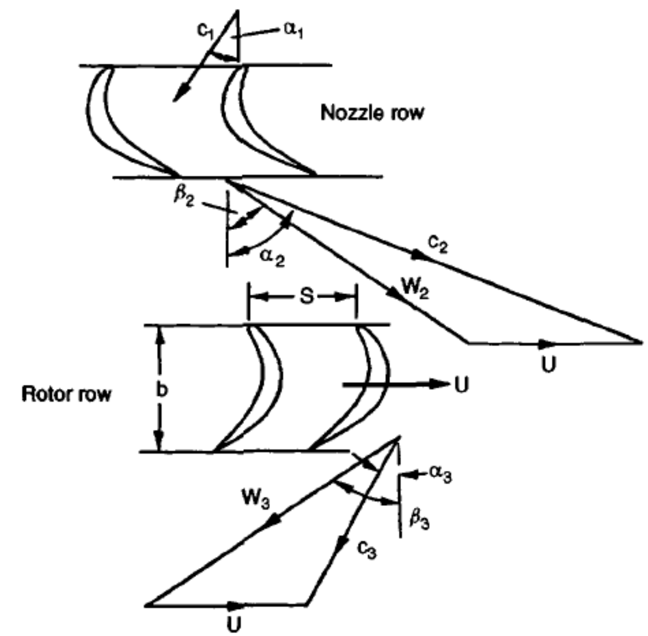
<u>Direct method based on lumped parameter approach</u>:

→ Mass, momentum, energy balances

$$\rho_1 V_1 S_1 = \rho_2 V_2 S_2$$

$$\rho_2 V_2^2 S_2 - \rho_1 V_1^2 S_1 = -P_2 S_2 + P_1 S_1 + \int_{S_l} -P\vec{n}\cdot\vec{\imath}\, dS + \int_{S_l} \vec{\tau}\cdot\vec{\imath}\, dS$$

$$\left(h_2 + \frac{V_2^2}{2} + g\cdot z_2\right) - \left(h_1 + \frac{V_1^2}{2} + g\cdot z_1\right) = l + q$$

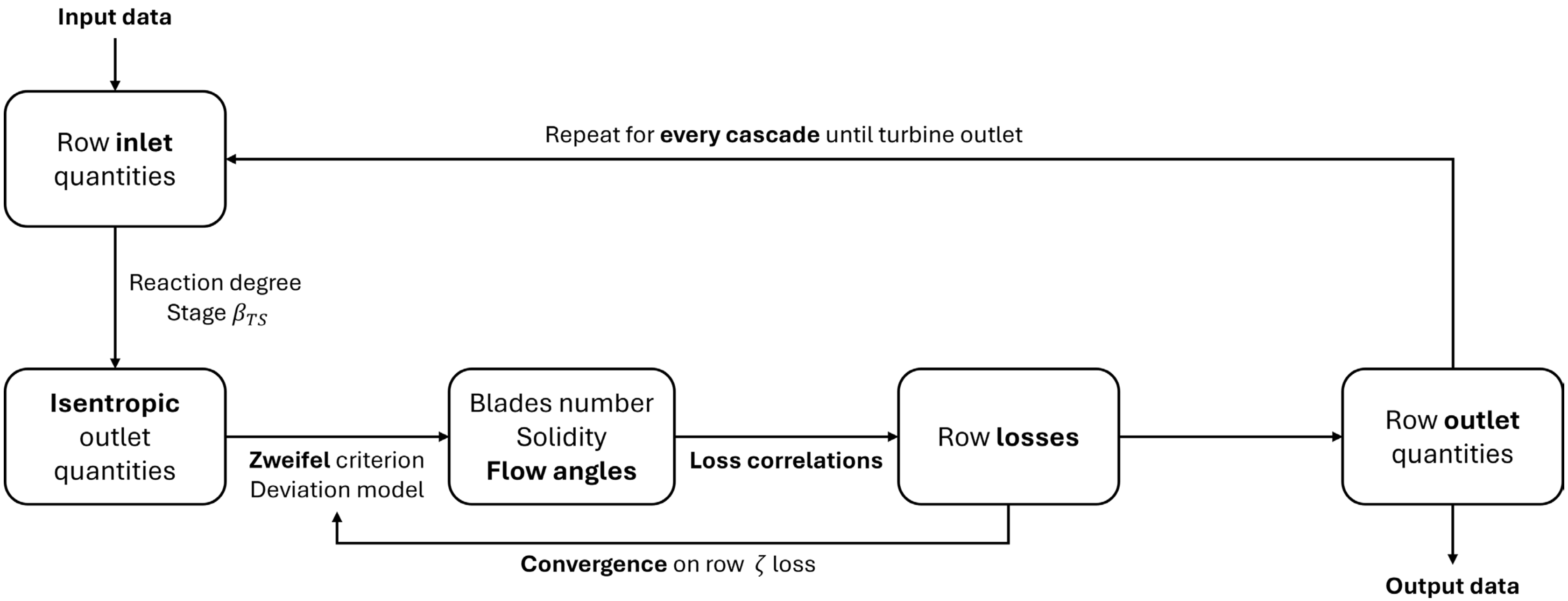


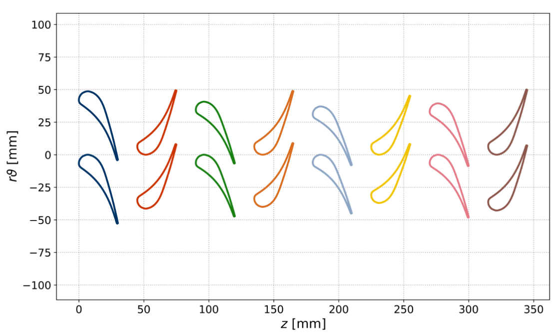
→ **Loss** correlations for axial/radial machines (Craig-Cox, Traupel, Lieblein, etc…)

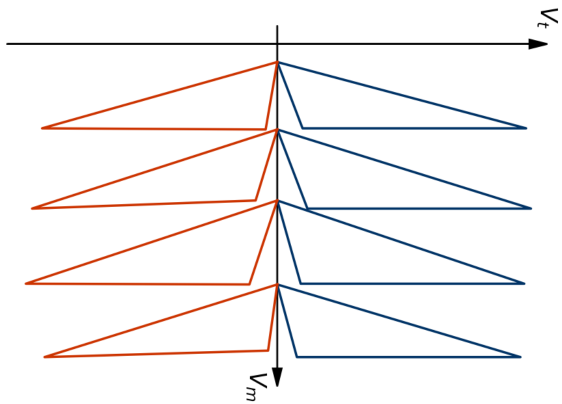
→ **Dev**iation/**inc**idence correlations (Ainley-Mathieson, Vavra, Lieblein, etc…)

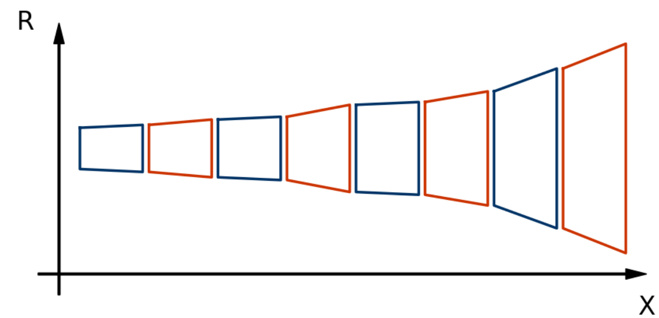
→ Corrections for loss/dev in transonic and supersonic flows (Deich – post-exp dev)

Mean-line design

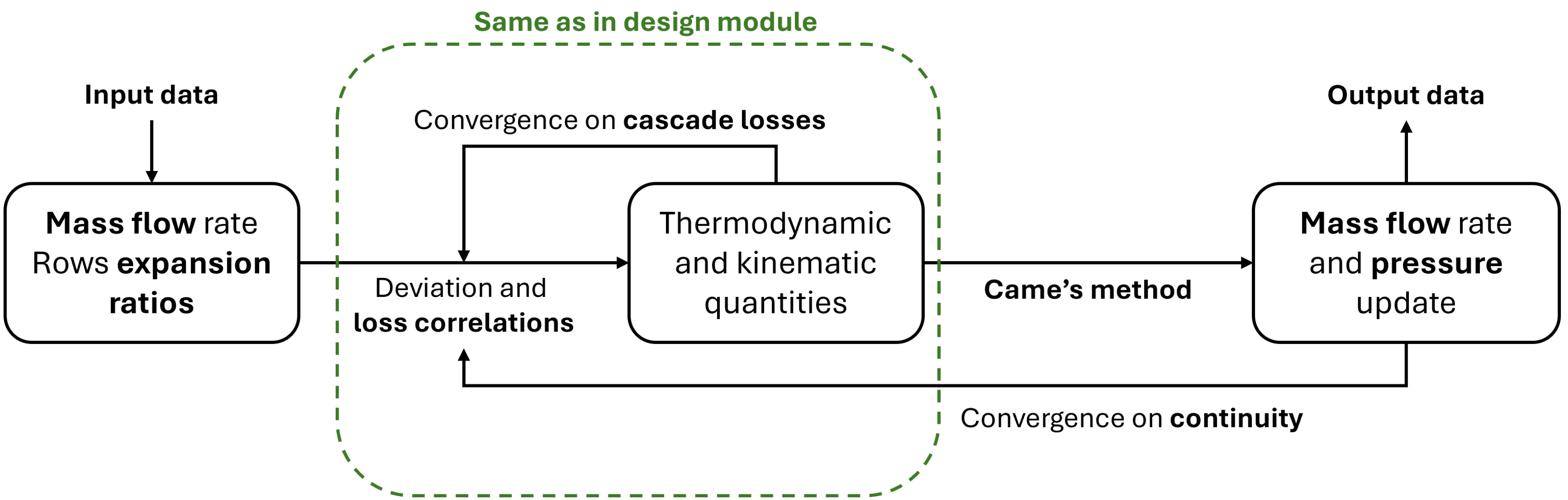


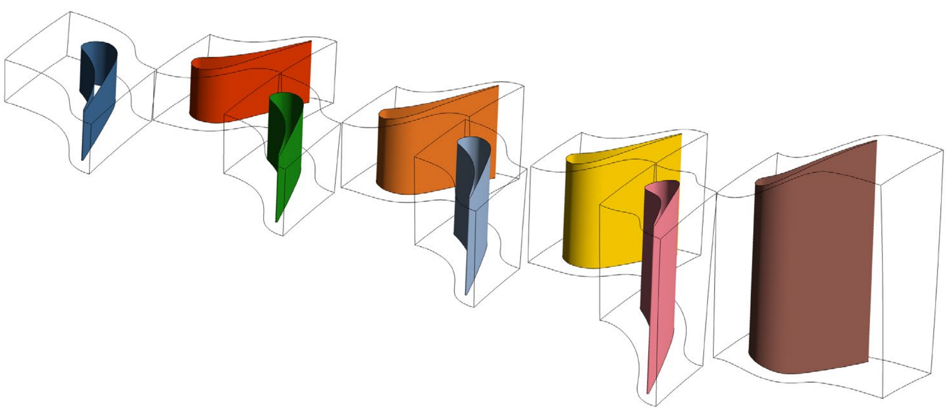


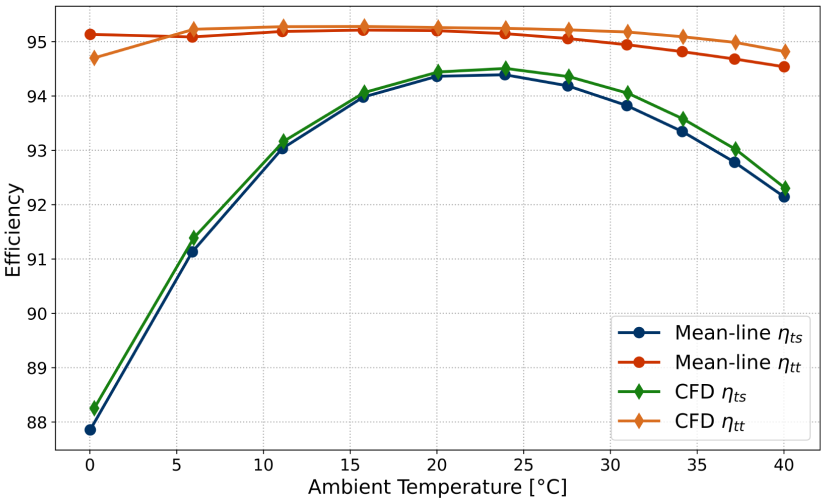




Mean-line analysis in off-design conditions



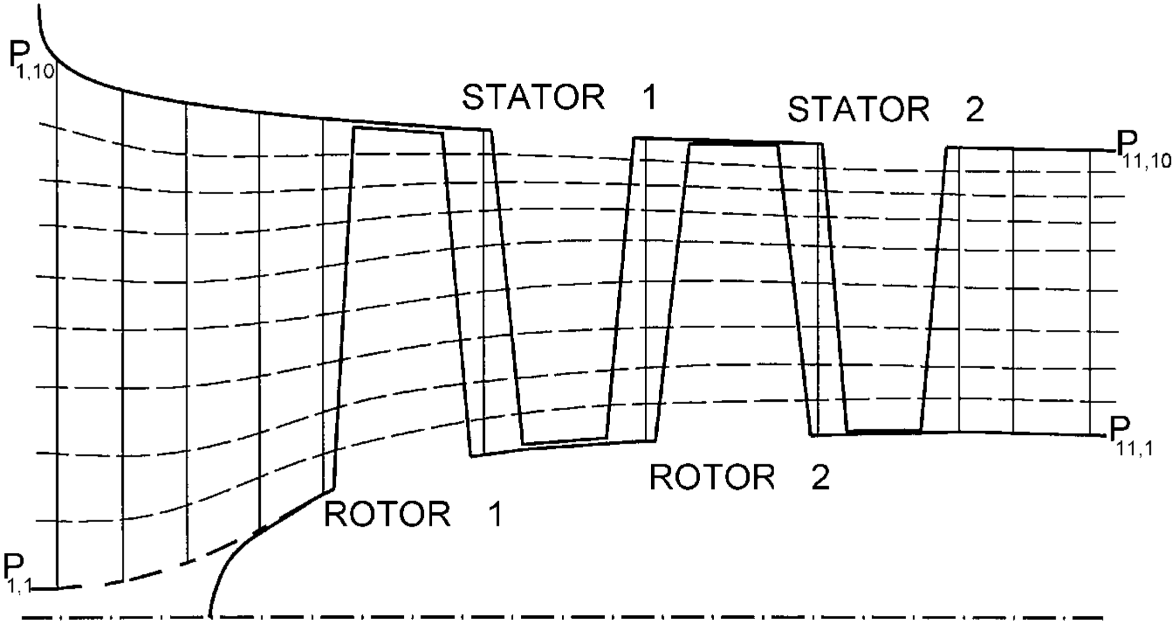




Spanwise models

Channel and streamline-curvature methods

✓ Generalization of **radial equilibrium equation**



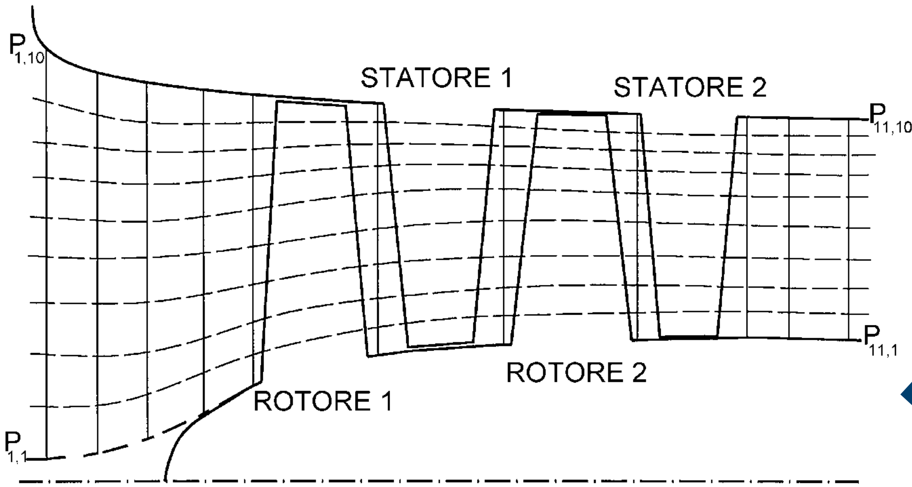
✓ Quasi-3D solution, generalized radial equilibrium:

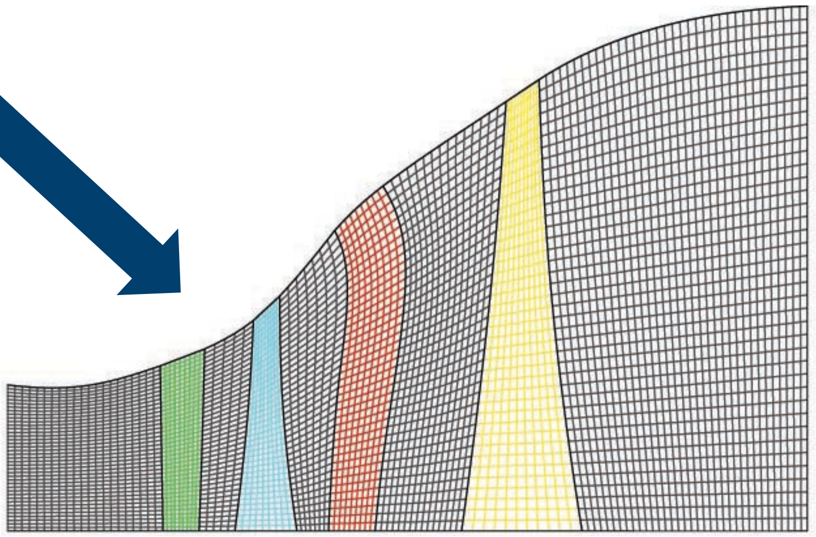
$$V_a \frac{\partial V_a}{\partial r} - V_a \frac{\partial V_r}{\partial z} + \frac{V_t}{r} \frac{\partial (r V_t)}{\partial r} = \frac{\partial h_T}{\partial r} - T \frac{\partial s}{\partial r}$$

- spanwise total enthalpy and entropy gradients → euler work + correlations
- spanwise streamline curvature → source term from continuity equation

Advanced throughflow concept

Distributed flow solution over an axisymmetric domain





Crucial step required

from spanwise equation to calculation of local flow configuration, integrating the flow equations over a computational mesh

Computational Fluid Dynamics

What is CFD?

- Solving generalized flow equations making use of numerical schemes to treat the differential and integral terms, in absence of analytical solutions

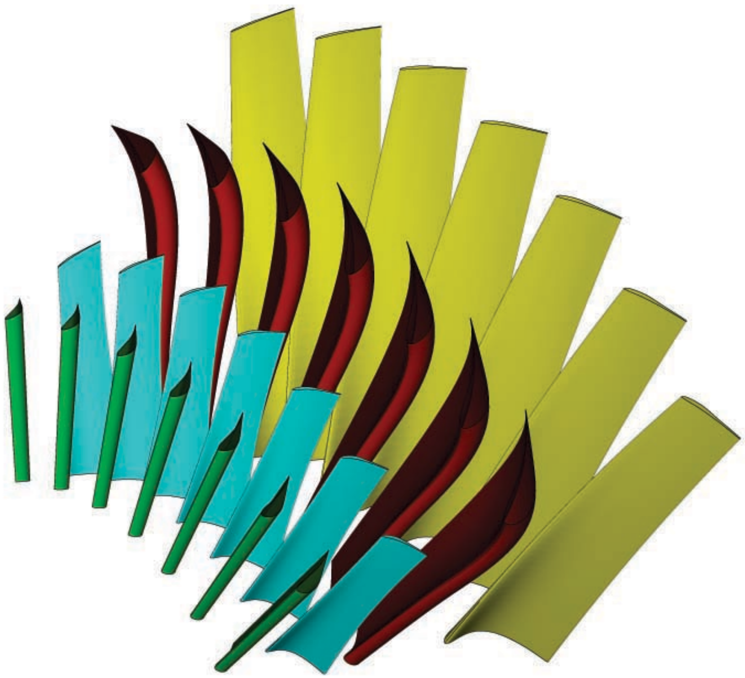
- Generally valid Navier-Stokes equations describe fluid flows: second-order, non-linear, prone to instability

- The complex set of **partial differential equations** are (approximately) **solved on a geometrical domain** divided into small elements, i.e. on a **mesh**

CFD-based Throughflow models

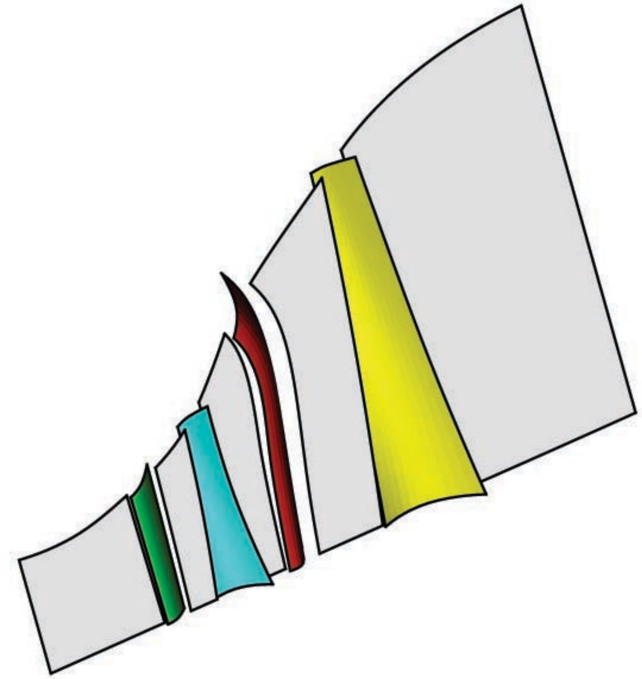
CFD-based conservative approach

Multistage turbomachine
3D (possibly unsteady) CFD

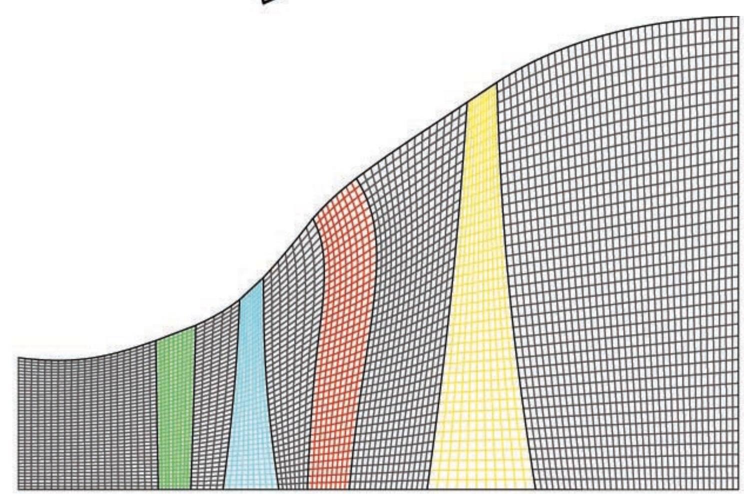


Blades replaced by mean surfaces

axisymmetric flow assumption



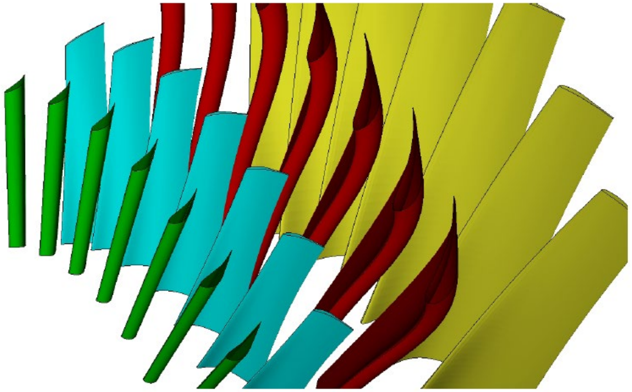
Mean surfaces projected on the meridional plane:
2D axisymmetric CFD approach

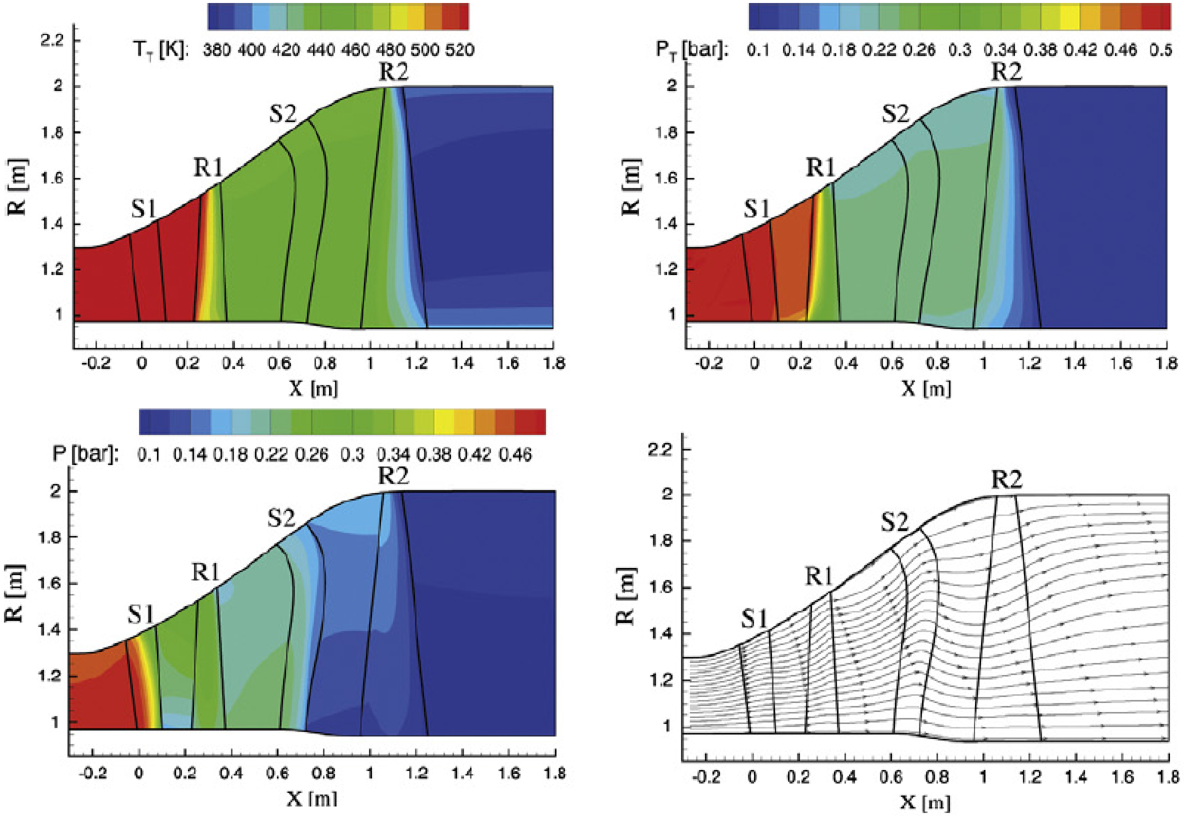


Throughflow model: LP steam turbine

Transonic application (β = 5)

- transonic flows at stators and rotor exit
- thermodynamic quantities distribution
- 3D kinematics solved on the meridional plane

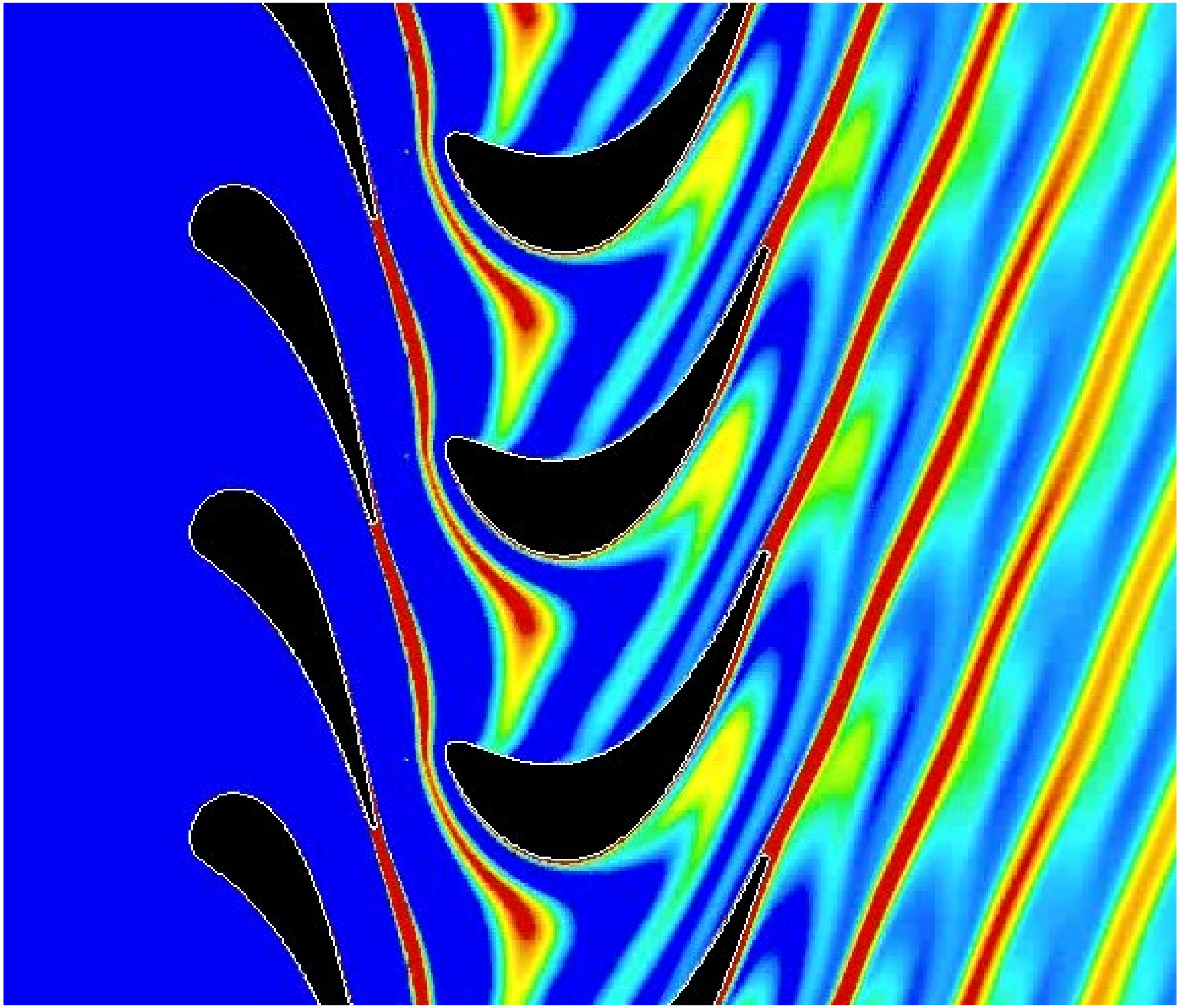




Fully 3D & Time-resolved Models: Computational Fluid Dynamics

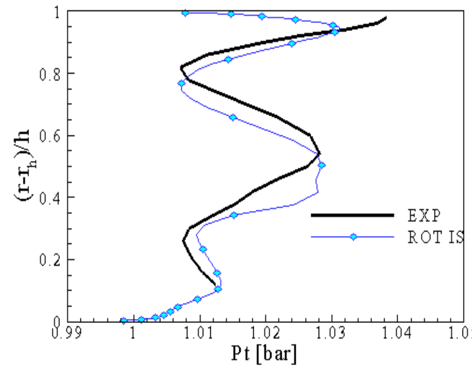
Coupled stator-rotor simulations

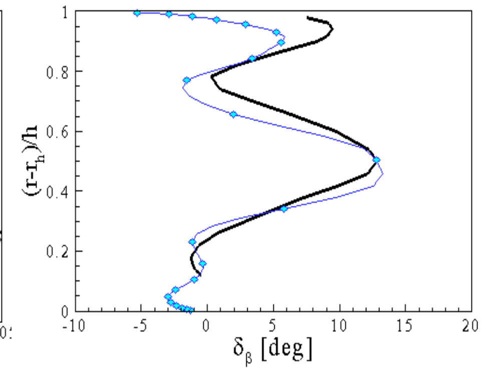
Examples of actual flow configuration - entropy generation in HP gas turbine

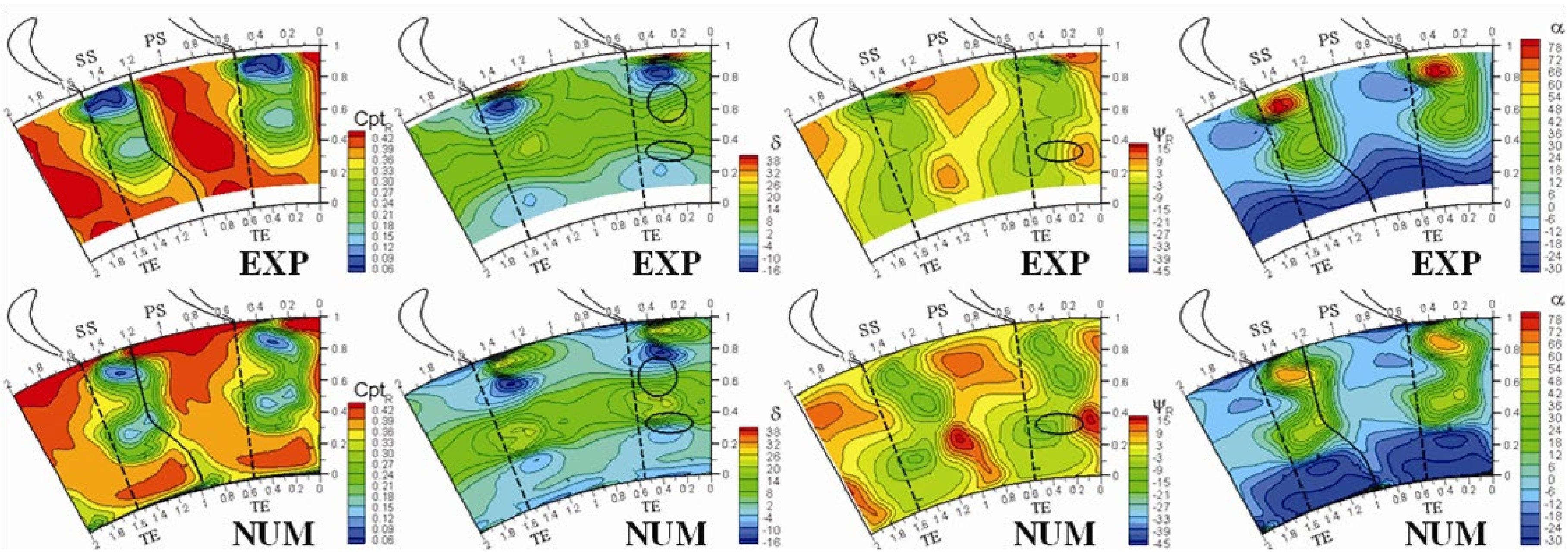


Fully-3D coupled model with experimental validation

- Unsteady calculation of the flow in a stator-rotor full stage with sliding mesh
- Flow physics well captured; computed efficiency within 1% of experimental one







Giacomo Persico –Politecnico di Milano

Is CFD suitable for design?
AI-based shape optimization

Surrogate Evolutionary Shape-Optimization

Shape Optimization: to minimize an OF using geometry as design parameters

Evolutionary Optimization – Genetic Algorithm:

✓ Direct: no need of problem inversion, only need direct CFD tools

✓ Heuristic: requires statistical relevance (→ high cost)

Combined with **Surrogate** models to tackle computational cost

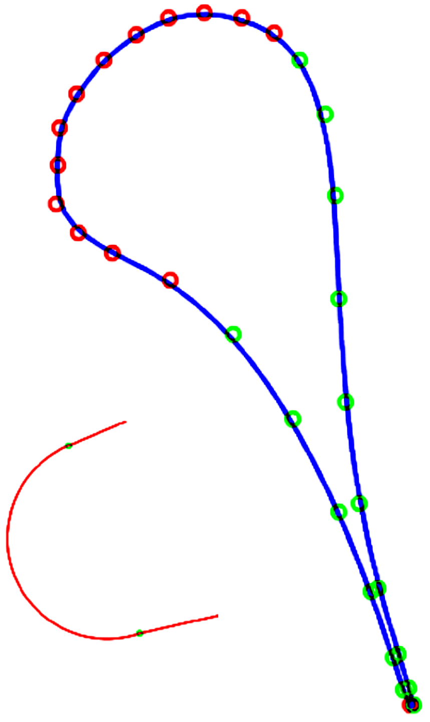
Briks

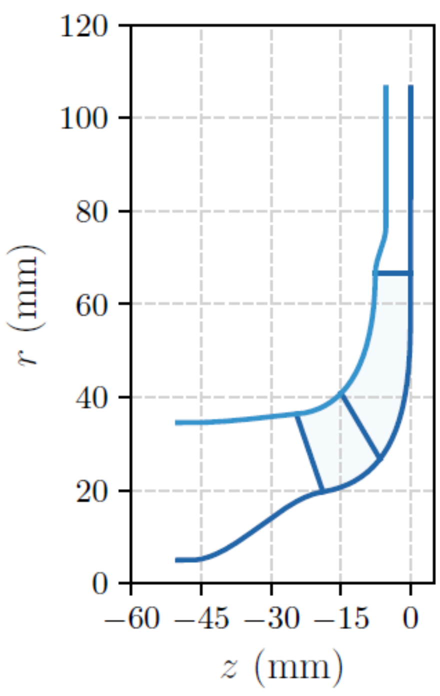
Geometry parametrization – B-Splines for profiles or CAD-based shapes

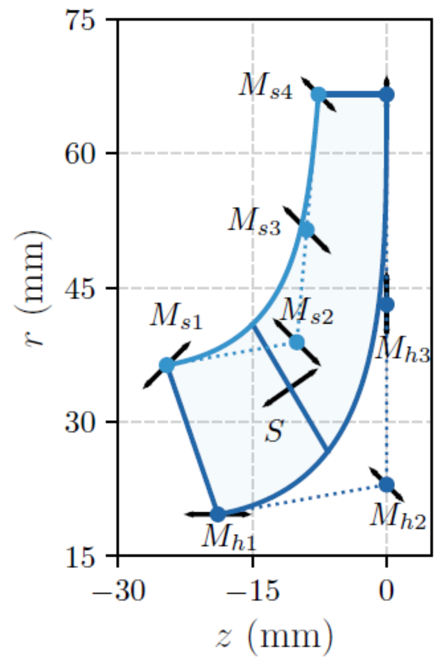
Concept: geometry as succession of regular lines identified by **Control Points**

B-Spline cubic lines: C^2 smoothness, identified by 4 CPs, computed recursively

Bezier cubic lines: C^2 smoothness, identified by a few CPs







Briks

Surrogate model

10^4 OF evaluations required by GA, CFD runs are expensive

→ **surrogate models** to speed-up convergence

Surrogate: function that mimics the 'response surface'

→ GA **only** applied to the interpolated surrogate model

Surrogate has to be reliable

→ **Initializaton** (DoE) and **Tuning**

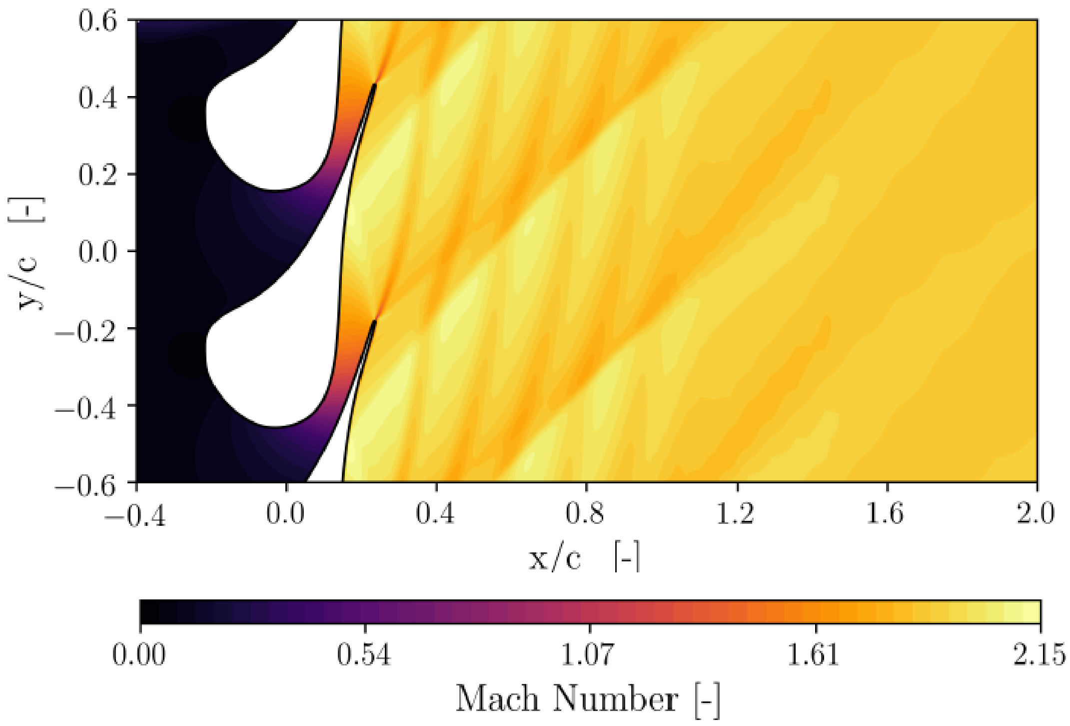
Exercise of Design: converging-diverging cascade

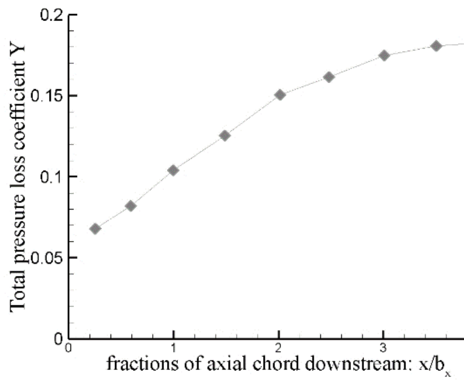
Supersonic converging-diverging cascade (M_{OUT} = 2.1) for axial ORC turbine (MDM)

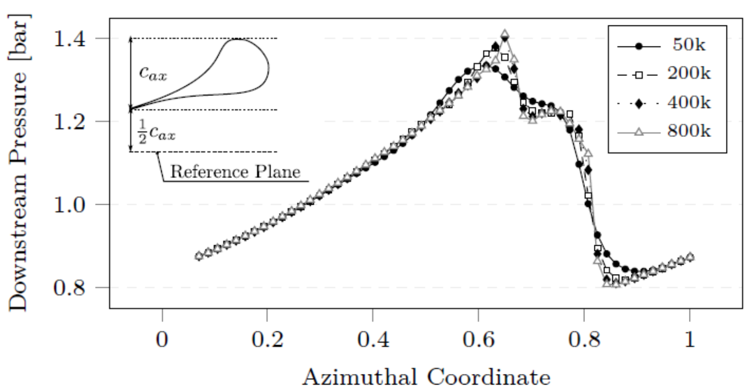
Strong shocks on Suction Side and on TE (fishtail)

dramatic raise of loss due to shock mixing downstream

time-periodic forcing on the subsequent rotor







Blade Shape Optimization

Supersonic converging-diverging cascade of axial ORC turbine (MDM)

Objective Function

Standard deviation of static pressure half a chord downstream of the TE

→ Minimize shock, shock mixing loss, flow disuniformity in stator-rotor gap

Design Space

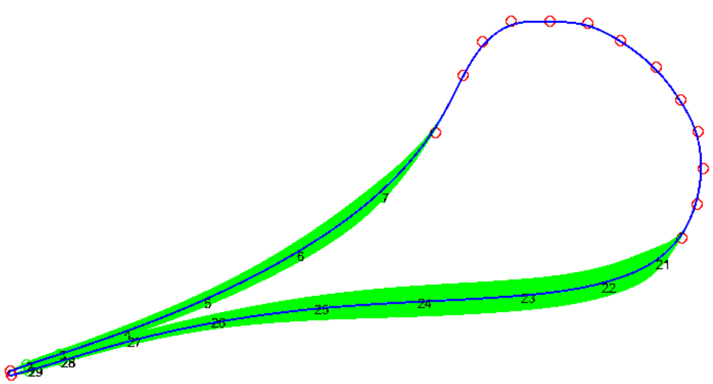
Parametric study on CP number and design space initially performed

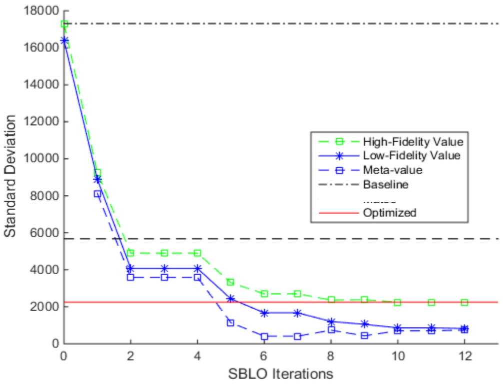
15 movable CPs in the rear blade section both on PS and SS

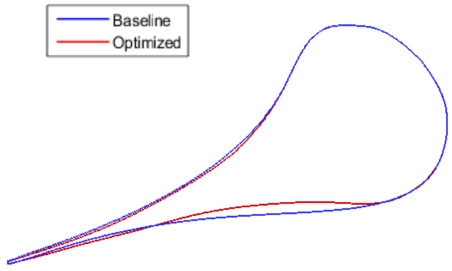
Optimization Process

Convergence attained (surrogate model becomes quickly reliable)

Limited computational cost: ≈ 20 h for a profile

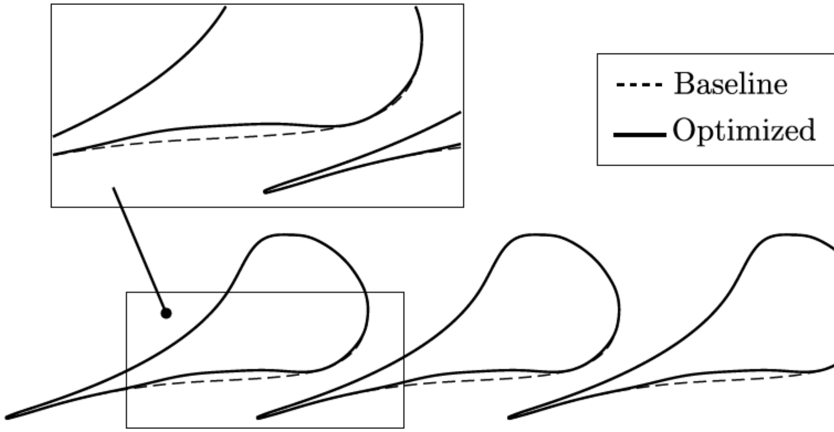


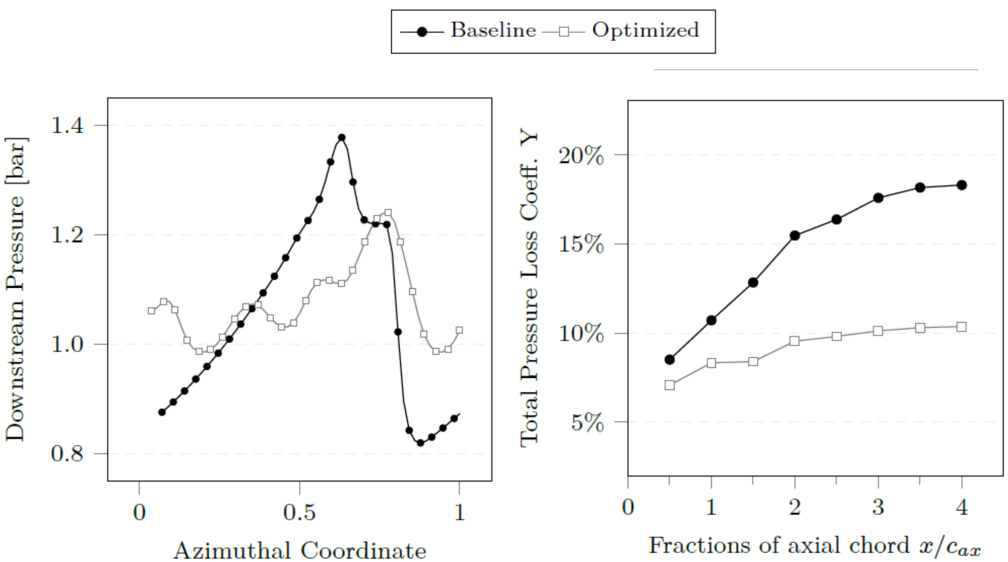


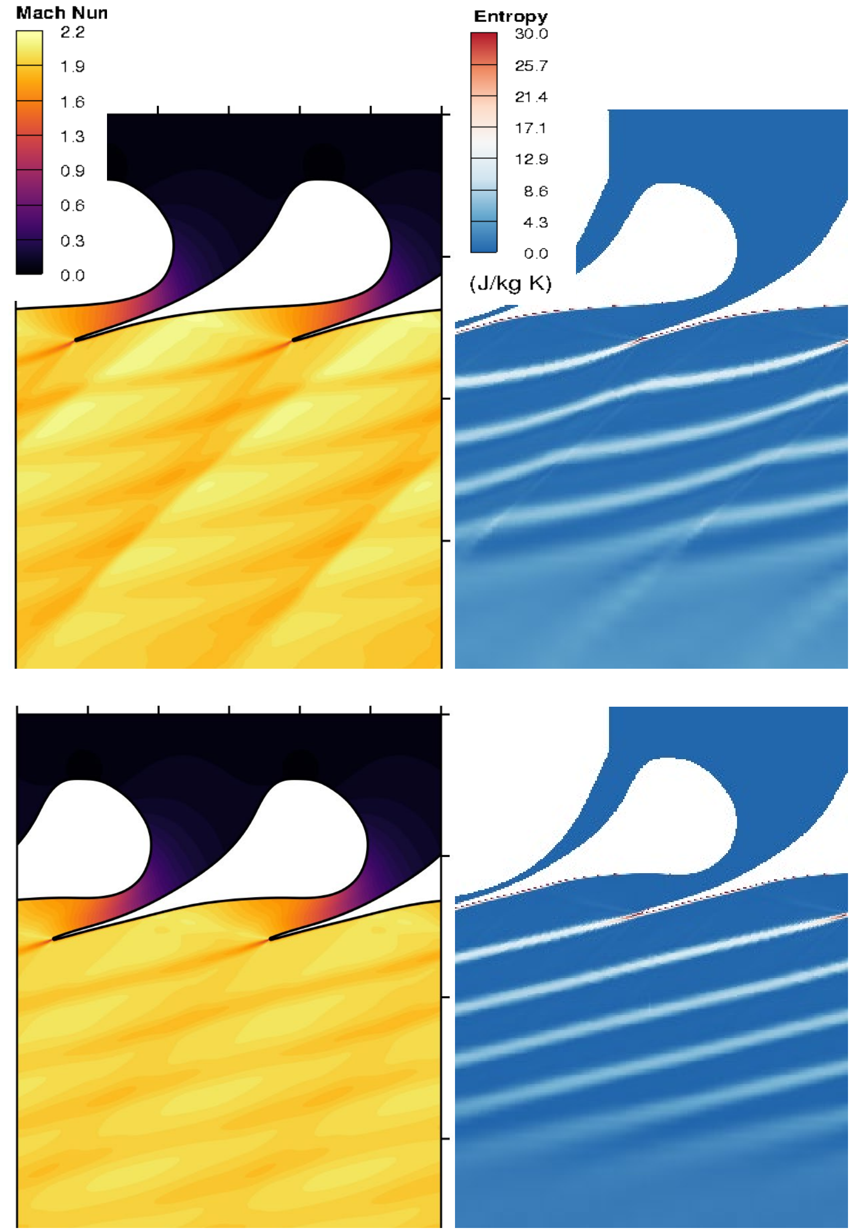


Exercise of Design I

Aerodynamic Analysis







Reduction of cascade losses by 50%

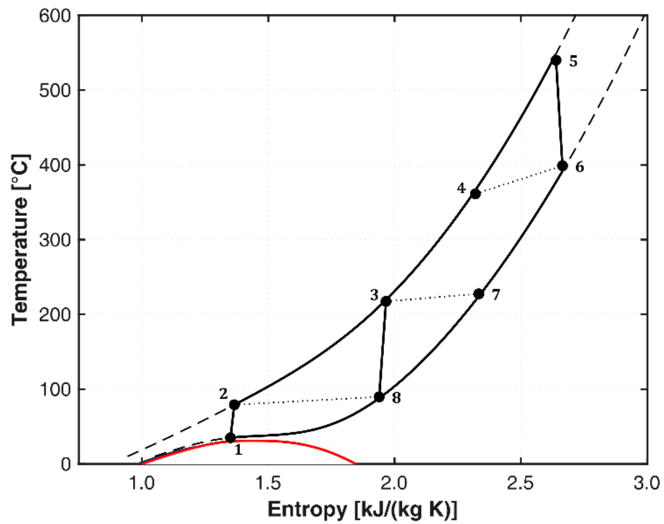
New challenges in turbomachinery modeling: advanced thermodyamics

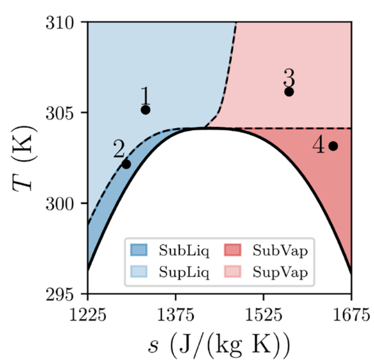
Non-ideal thermodynamics in sCO_2 compressors

For an ideal gas:

$$v_{id} = {}^{RT}/_{P}\ ;$$

$$\gamma = {}^{c_P}/_{c_v} = -\frac{v}{P}\left(\frac{\partial P}{\partial v}\right)_s = k$$





Close to the critical point:

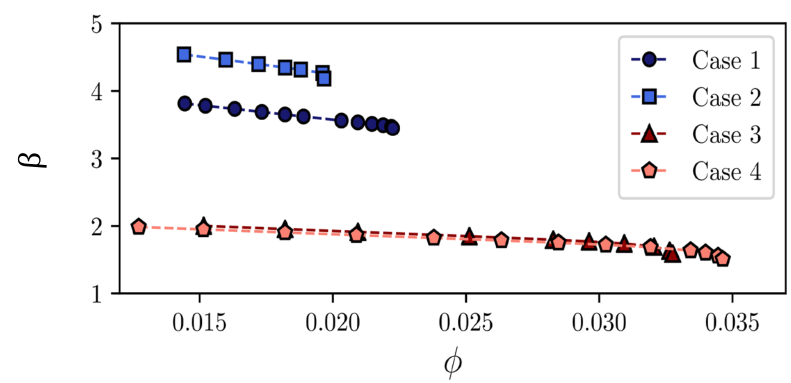
$$v \neq v_{id} \implies Z \stackrel{\text{def}}{=} {}^{v}/_{v_{id}} \ll 1\ ;$$

$$k \neq \gamma\ ; k = (T,s)\text{: } k \uparrow \text{as entropy} \downarrow.$$

Compressor head coefficient not bi-univocally related to the pressure ratio

$$\Psi = \frac{\Delta h_{tt,is}}{u_2^2} \approx \frac{\beta^{\frac{k-1}{k}} - 1}{M_{u2}^2(k-1)}\ :$$

$$k \uparrow, \beta \uparrow$$



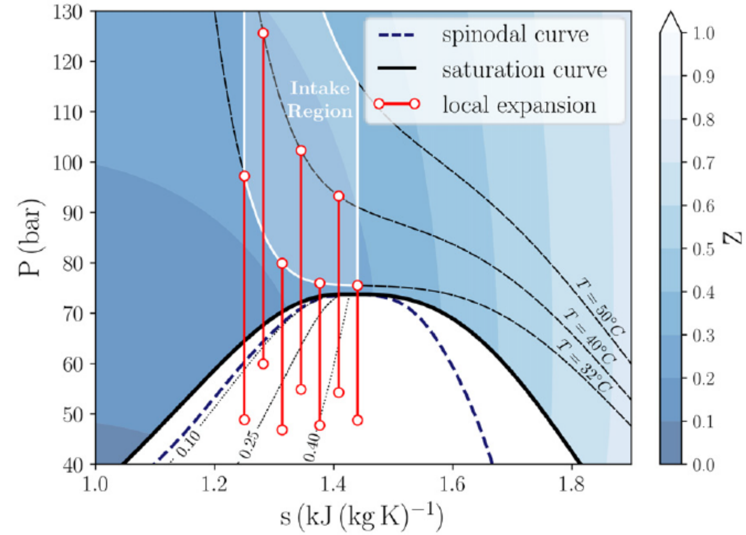
Romei et al., GT2021-60252

Phase change in sCO_2 compressors

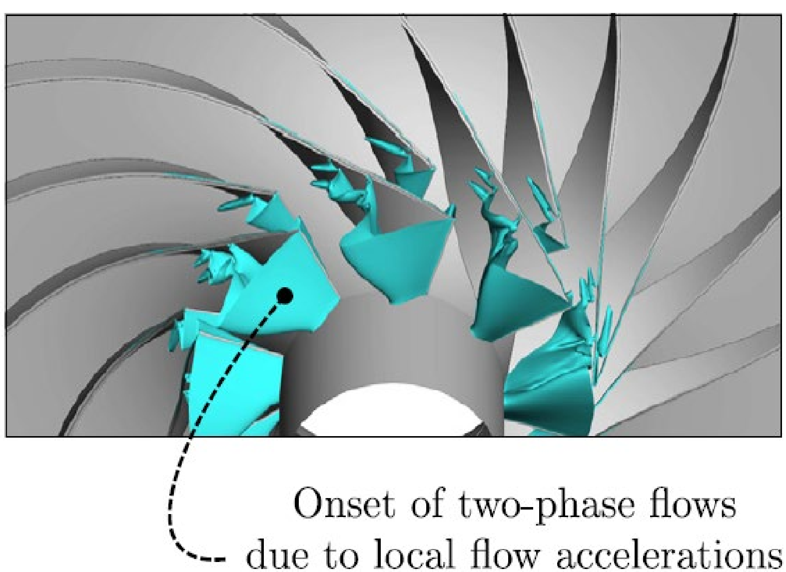
Acceleration at compressor intake

→ diving **into the two-phase dome**!

- ✓ Wide two-phase flow regions generated in the front part of the blades
- ✓ Severe drop in speed of sound at the onset of phase change
- ✓ Drop in speed of sound at phase change may cause anticipated choking

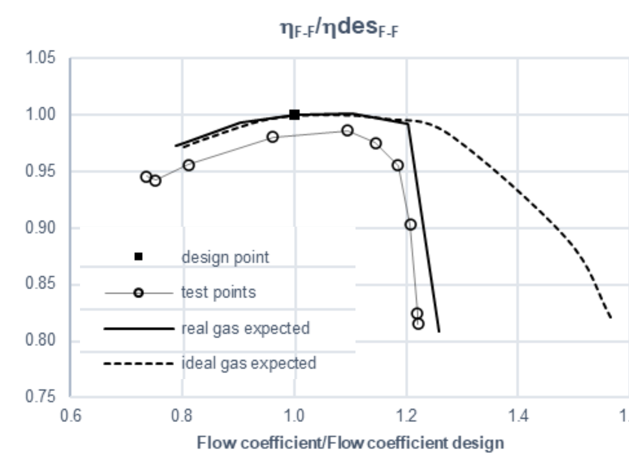


Persico et al., Journal of Eng. Gas Turbines Power 2021



Romei and Persico, Applied Thermal Engineering 2021

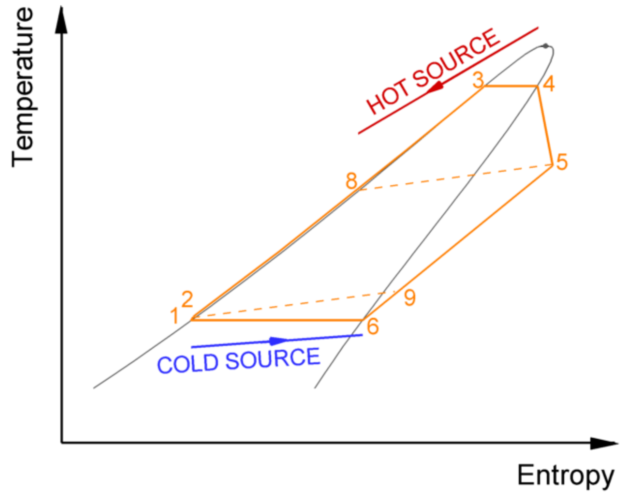
SCO2-FLEX compressor (EU, H2020)

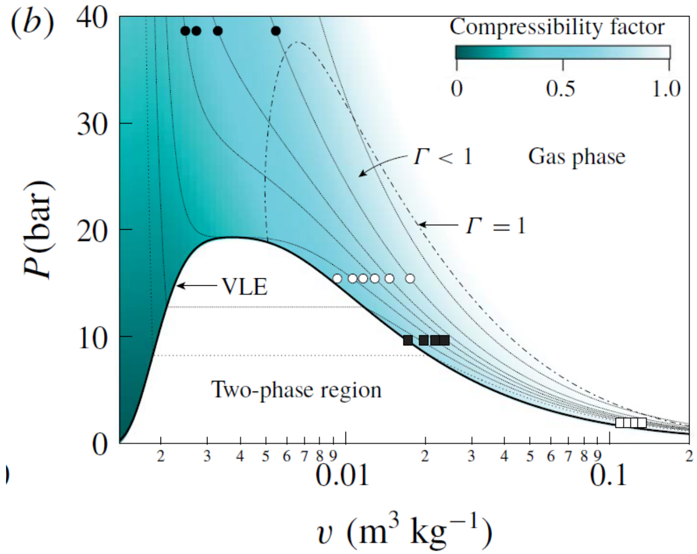


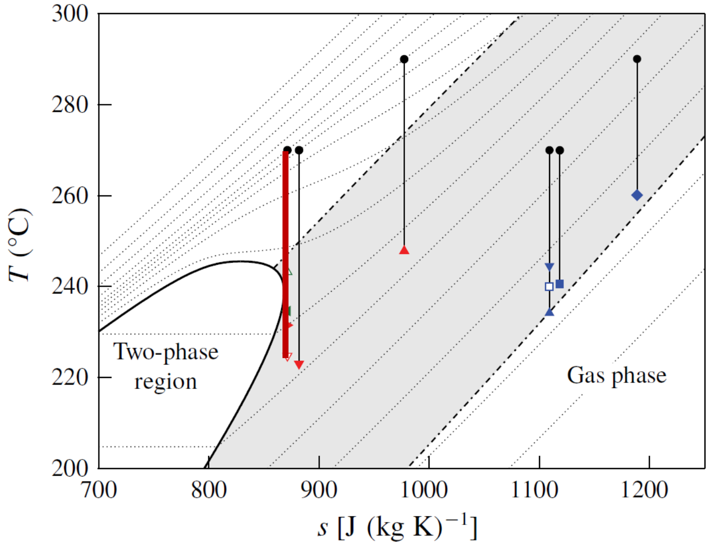
Toni et al., International sCO2 Power Cycles Symposium 2022

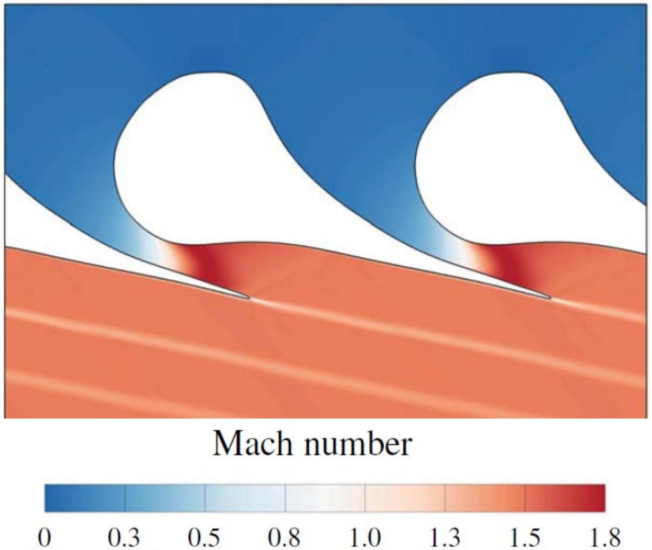
Non-ideal gasdynamics in ORC turbines

$$v \neq v_{id} \Longrightarrow Z \stackrel{\text{def}}{=} v/v_{id} < 1 \qquad \Gamma = 1 + \frac{\rho}{c}\left(\frac{\partial c}{\partial \rho}\right)_s$$









Romei et al., Journal of Fluid Mechanics 2020

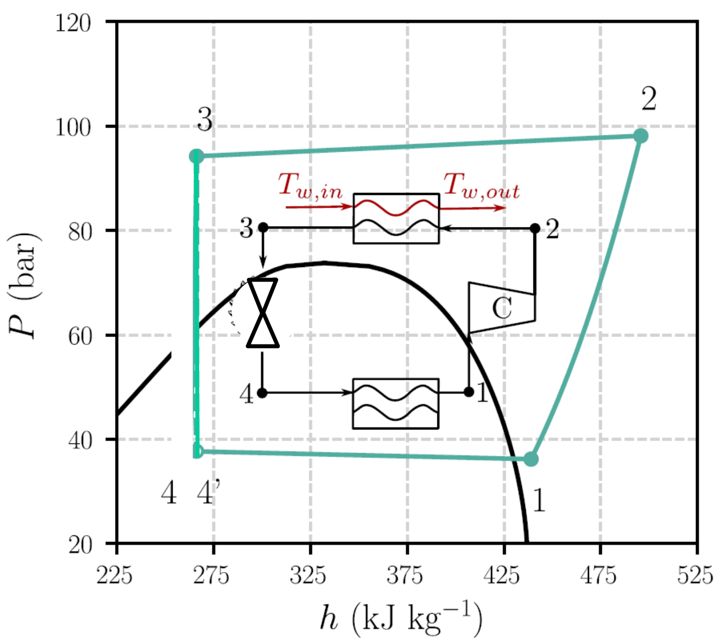
Two-phase expanders for trans-critical heat pumps

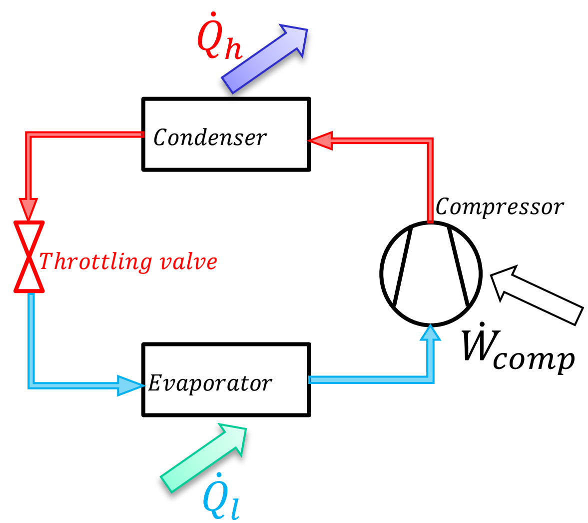
The expansion is normally achieved by a throttling valve, a cheap static component

The transformation is iso-enthalpic, but with a significant entropy generation

This is one significant source of thermodynamic loss for the cycle

An obvious potential for COP increase is to replace the valve with an expander





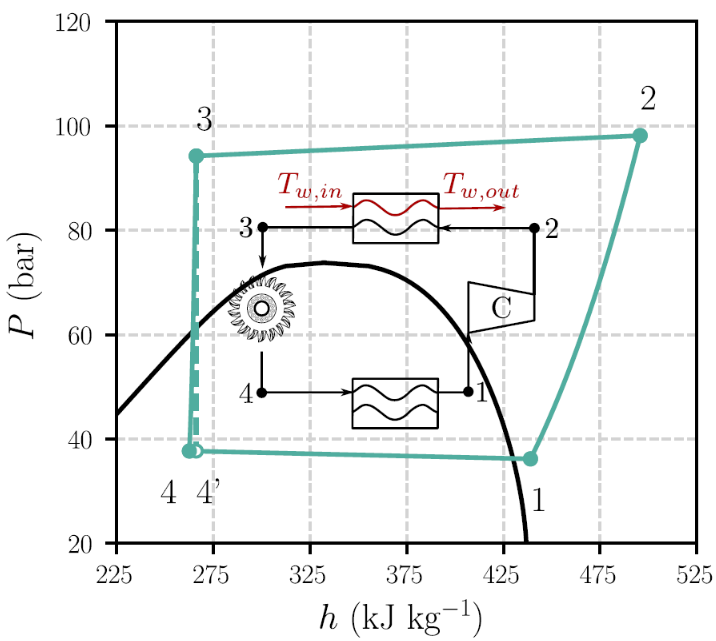
Two-phase expanders for trans-critical heat pumps

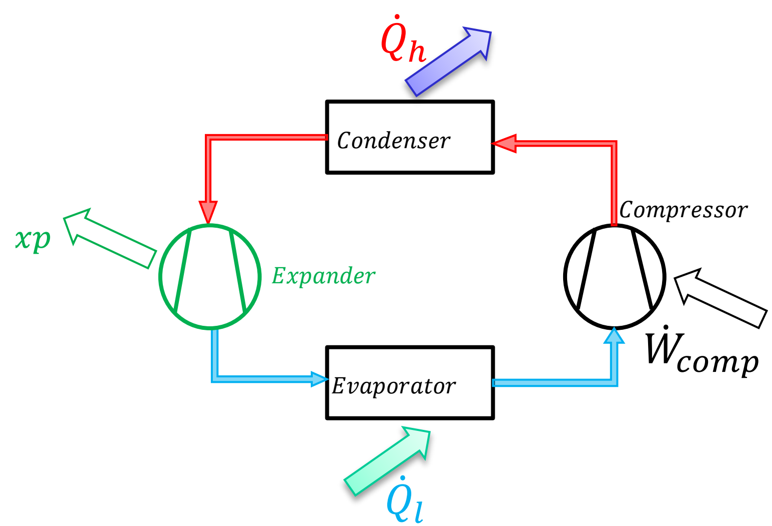
The power released by the expander reduces the overall cycle power requirement

The expander can be either volumetric or a turbomachine, depending on the plant capacity, volume flow, and expansion ratio

In any case, the expansion occurs at least partially within the two-phase region

This is a great source of complexity for design and optimization of the machine



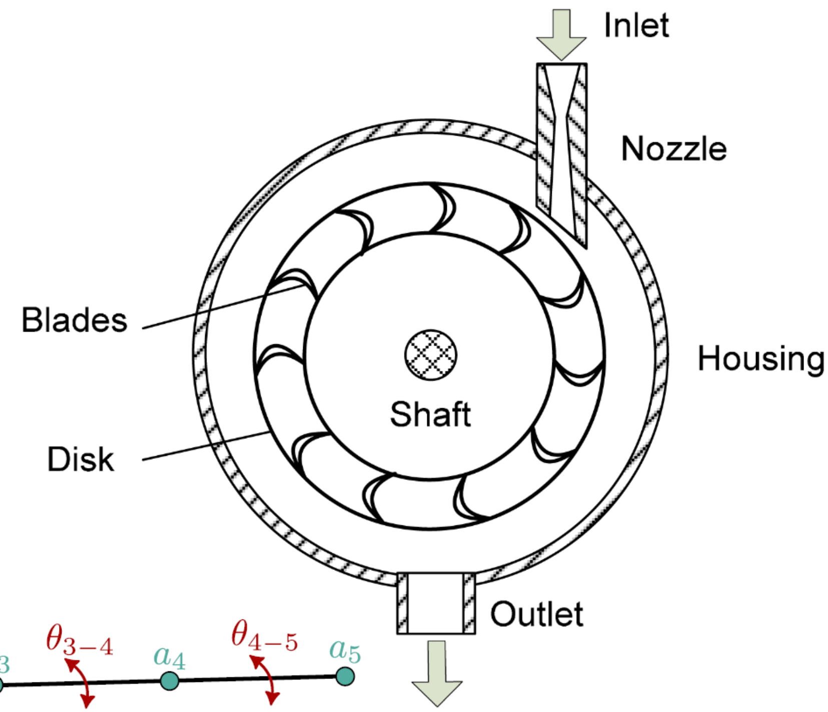


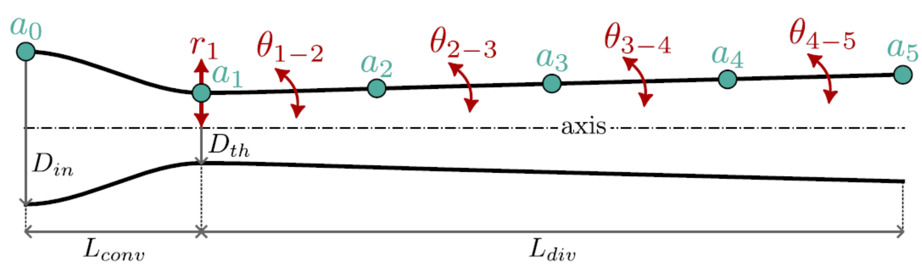
Exemplary turboexpander design
Pelton impulse turbine

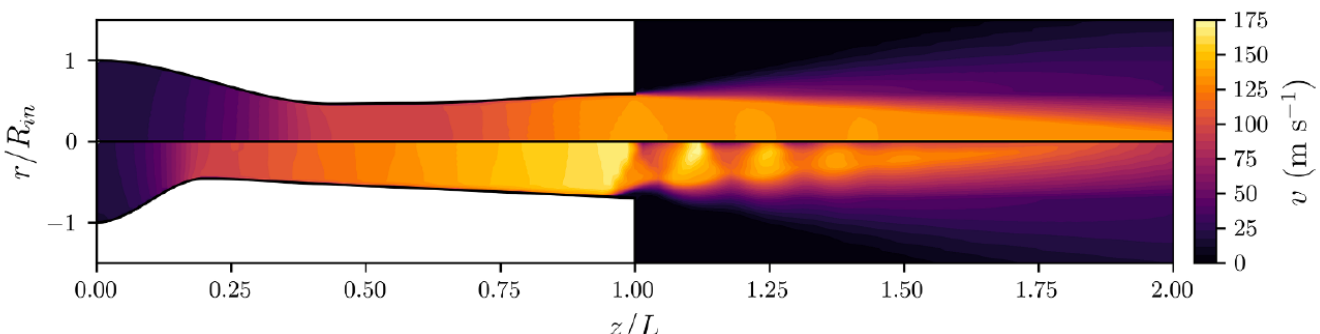
Impulse turbines feature expansions occurring solely across the nozzle

Two-phase nozzle most critical component

→ Shape-optimization performed to find optimal two-phase supersonic efflux







Kamali at al., Applied Thermal Engineering, 2024

Further challenges

High-fidelity turbulence simulations by Large Eddy Simulations and Direct Numerical Simulations: no more unfeasible with supercomputers!

Conjugate heat transfer calculations for cooled turbine blades

Leakage flows and secondary system modeling combined with flow path

Aeroacoustic phenomena correlated to turbomachinery

Thank you!

Any questions?

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