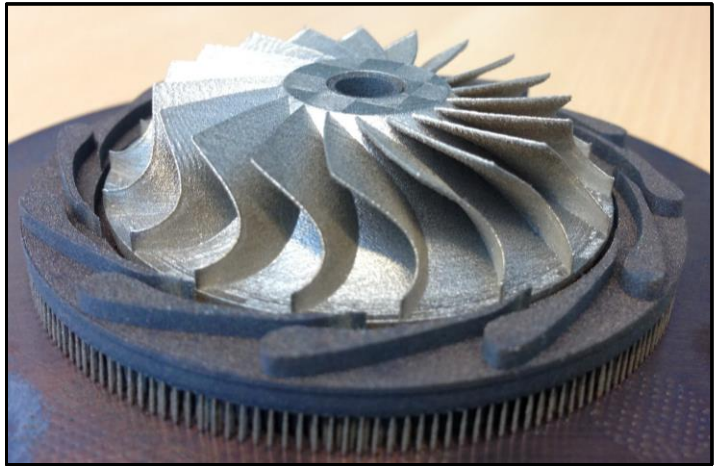
ORCHID Turbine

Fluid-dynamic design and characterization of a mini-ORC turbine for laboratory experiments

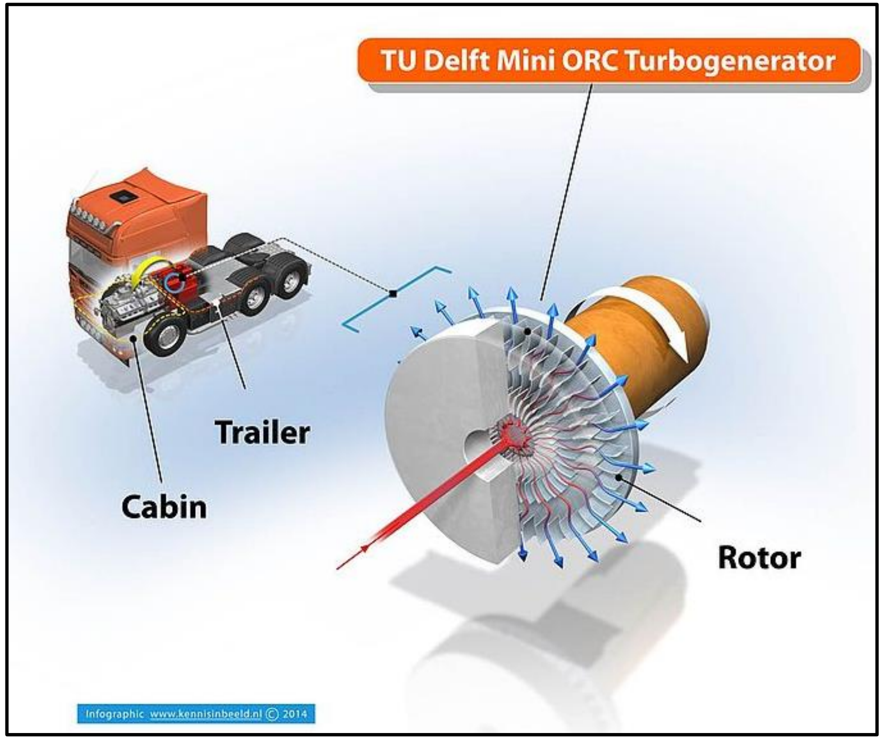
M. Pini, C. De Servi, **M. Burigana**,
S. Bahamonde, A. Rubino, S. Vitale,
P. Colonna

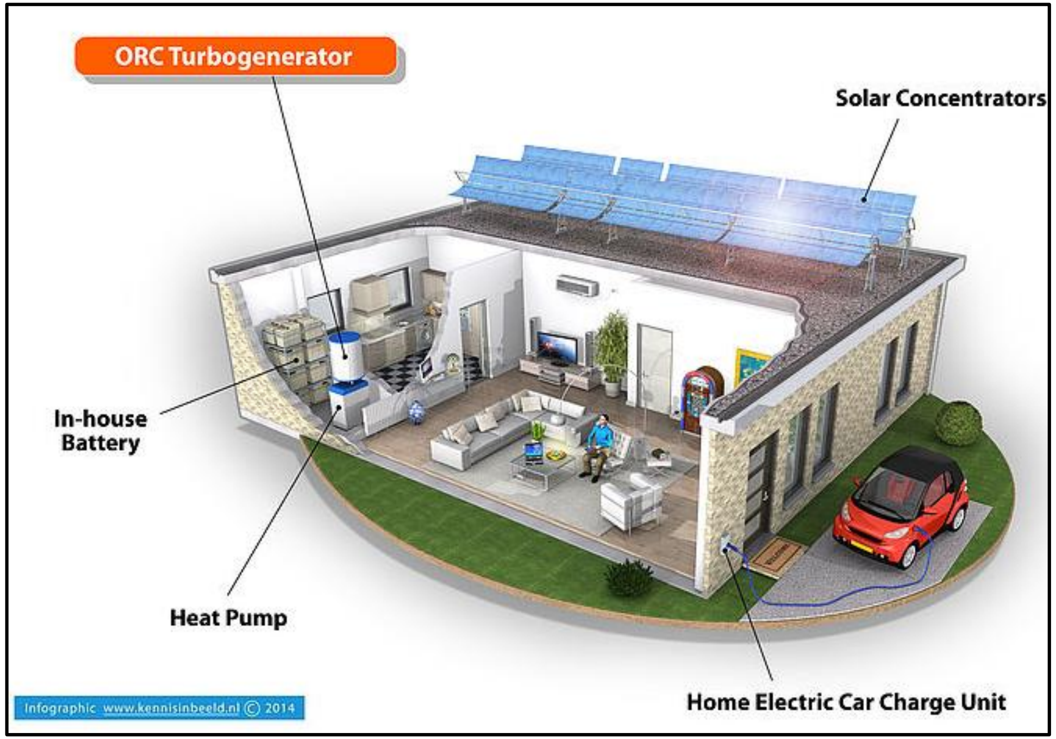
ORC2017 - 14/09/2017



Small-Power Capacity ORC Units

- Combined-Cycle Powertrains
- Zero-Energy Buildings





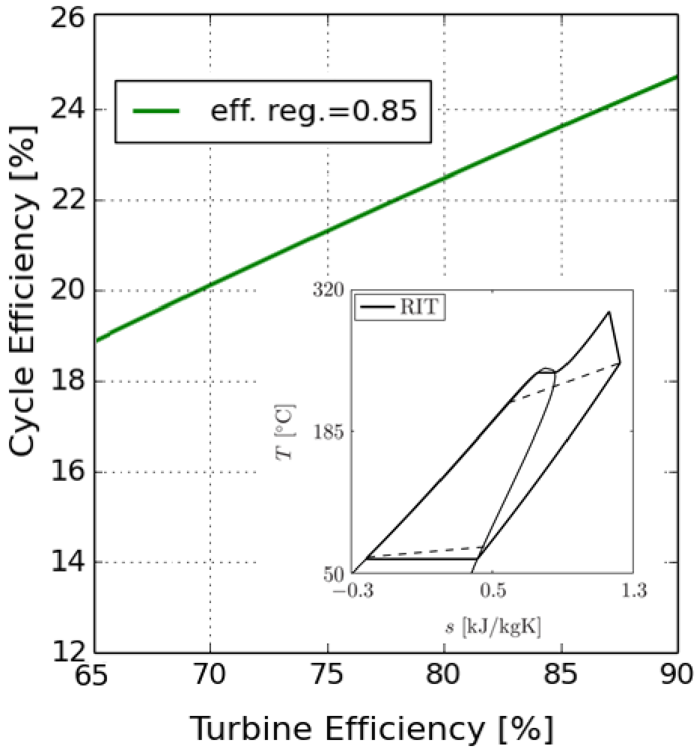
Problem Statement

$10\ kW_e$

Radial Inflow Turbine

- Challenging turbine design
    - High volumetric ratio
    - Non ideal gas behavior
    - Small dimensions
- No validated design guidelines
    - Loss models
    - CFD
- No industrial experience!

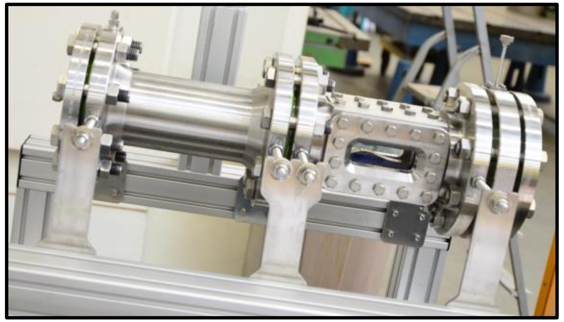
Turbine efficiency pays out!



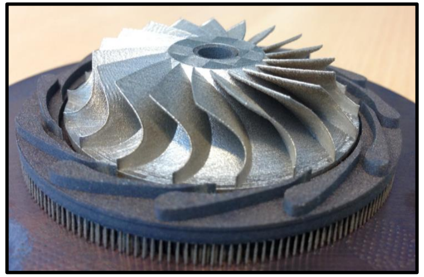
Our Envisaged Solution

ORCHID facility

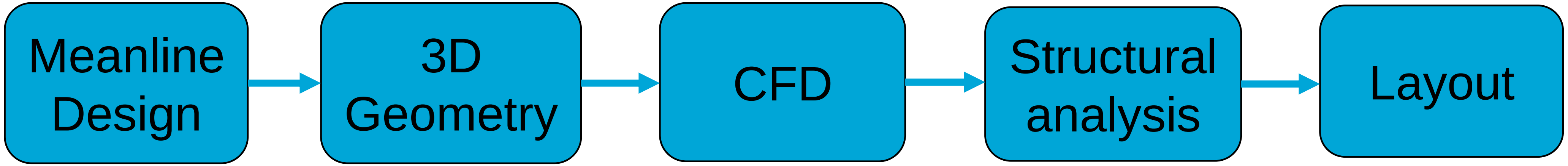
Planar de Laval nozzle



Turbine test section



FD Design Path for mini-ORC RIT

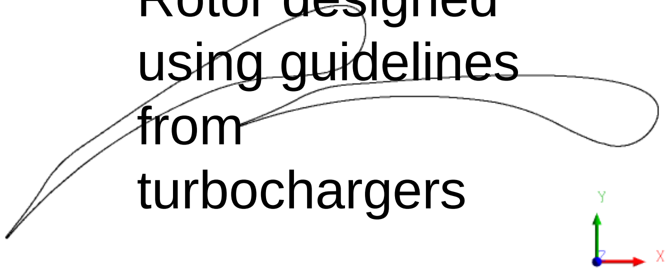

Meanline Design → 3D Geometry → CFD → Structural analysis → Layout

Siloxane MM

Radial-inflow

Stator designed by adapted MoC

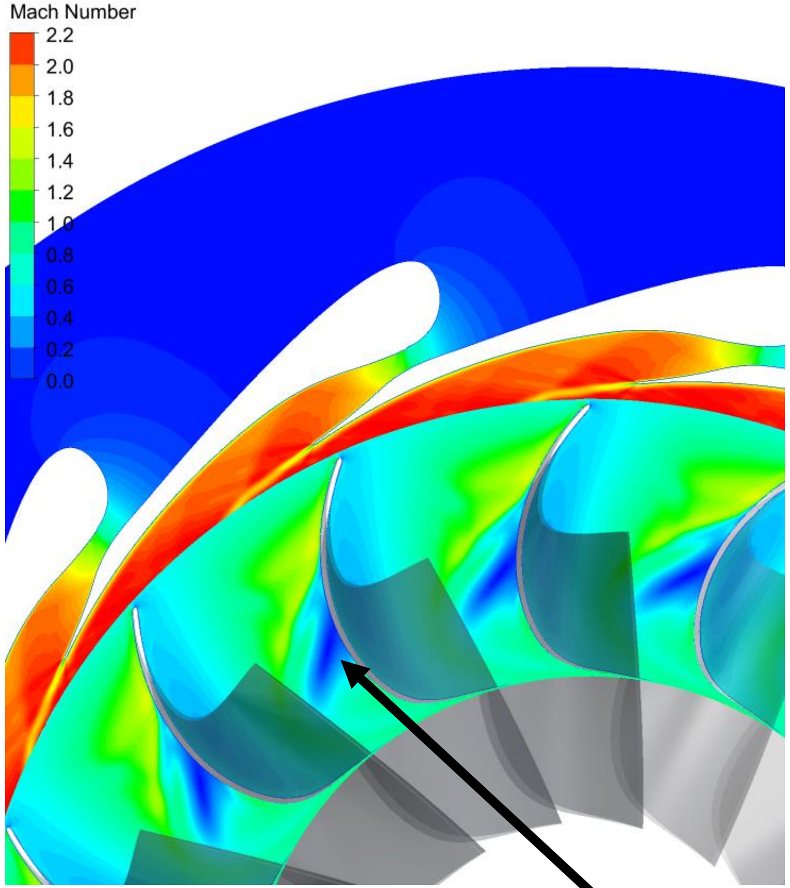
Rotor designed using guidelines from turbochargers

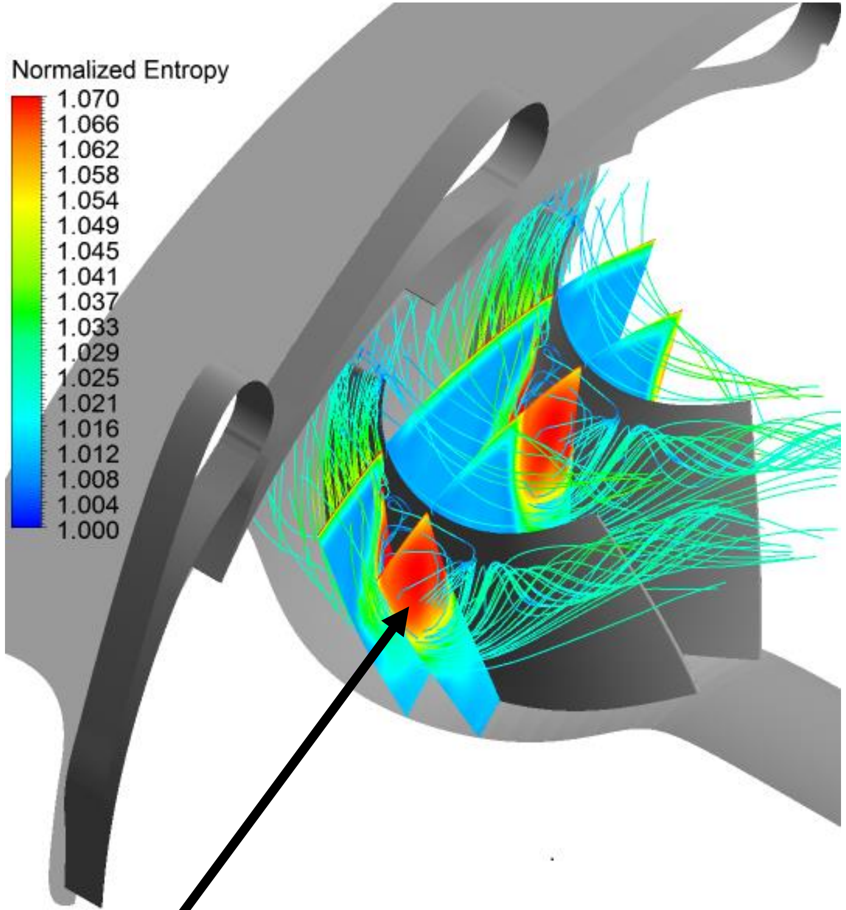


3D Mixing-plane with SST-kω

Centrifugal & Aerodynamic loads

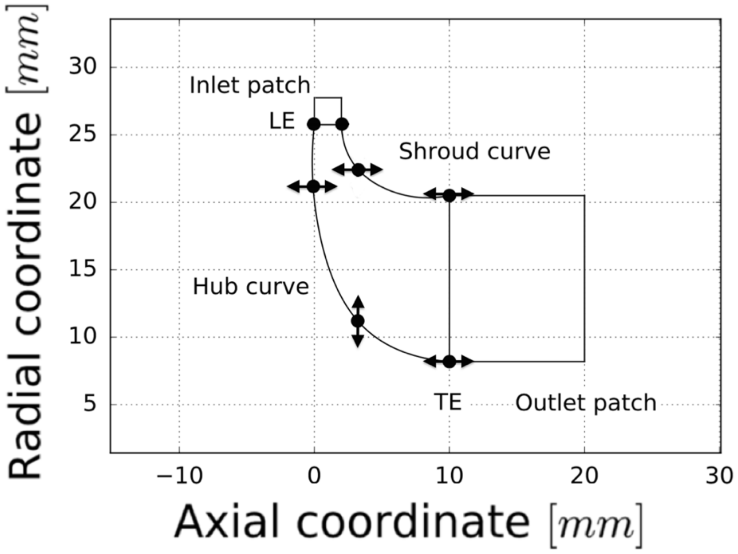
Resulting Turbine Design

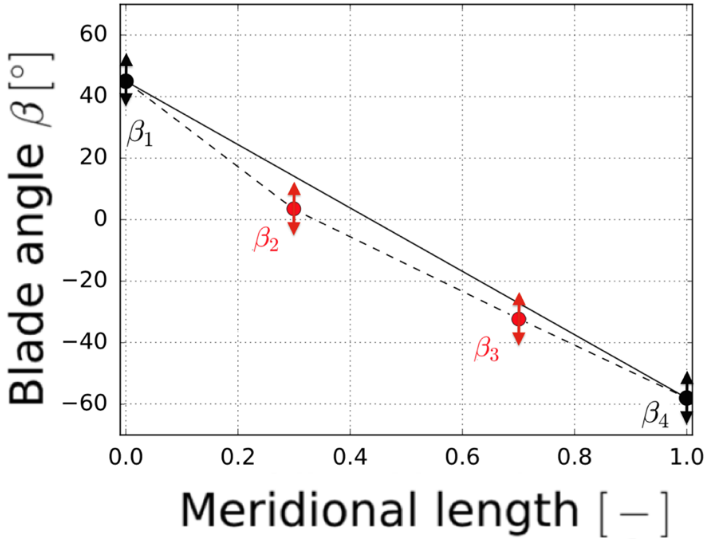


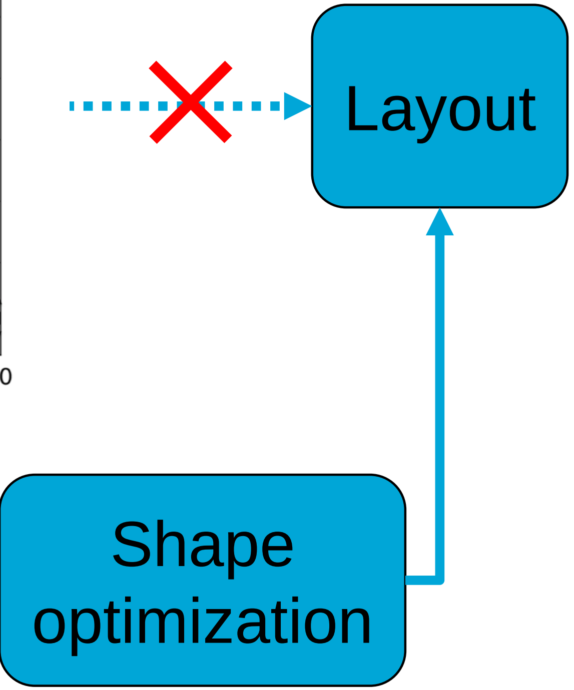


Flow separation

Exploiting Shape Optimization





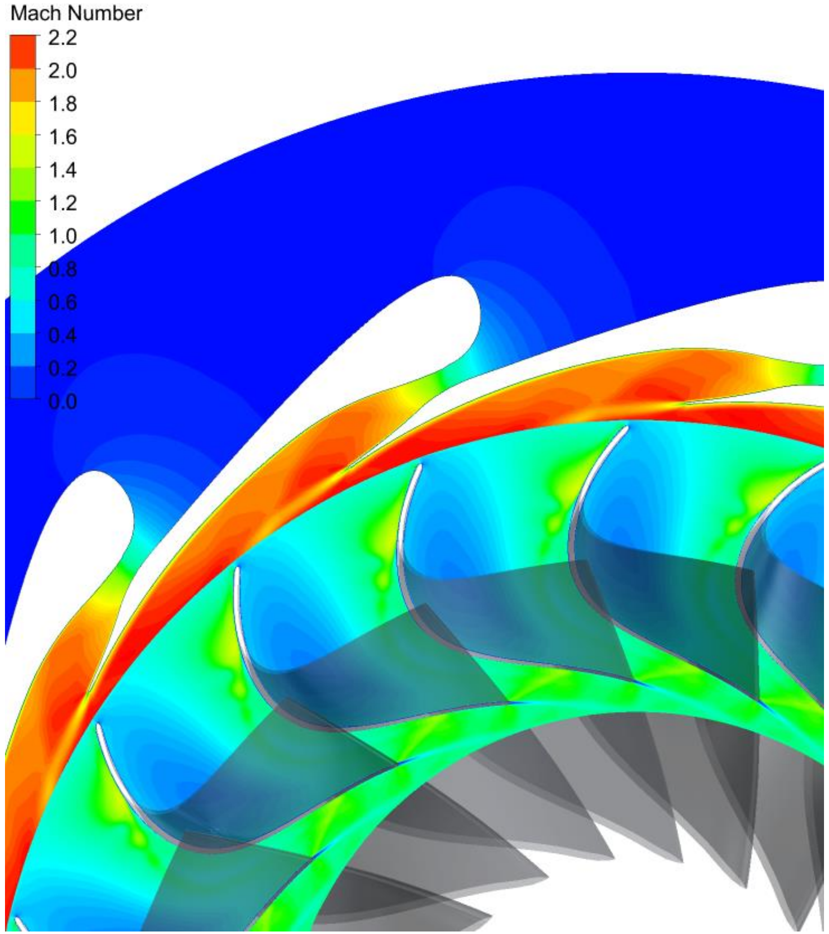


Layout

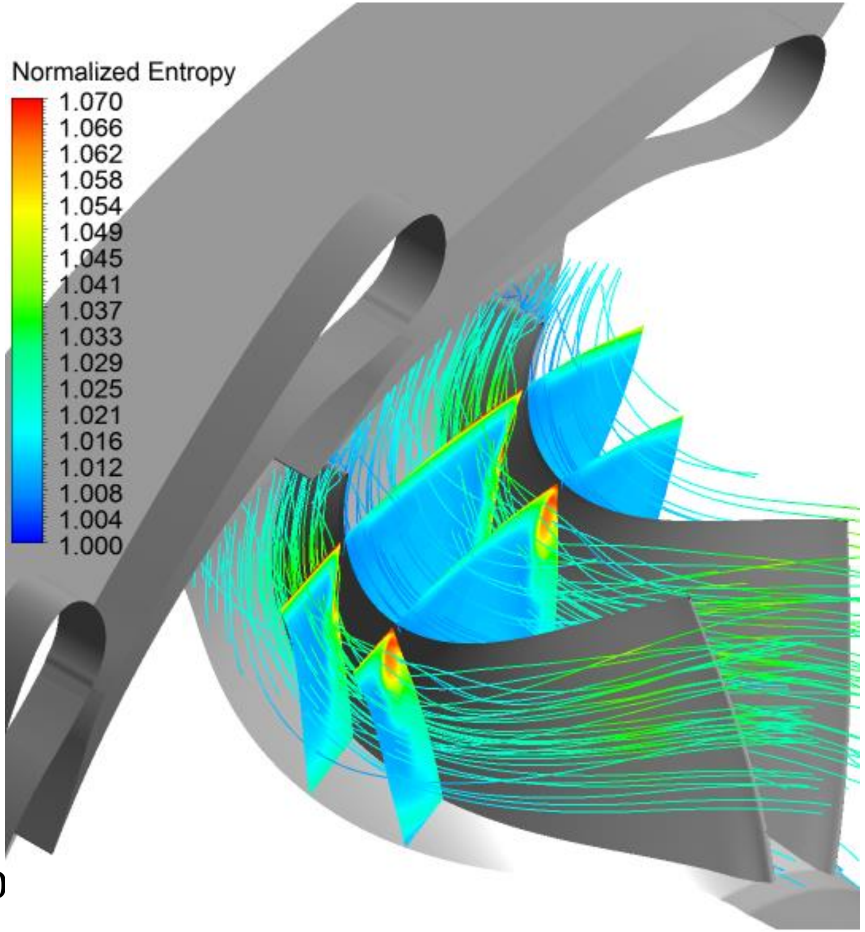
Shape optimization

1. 13 Design variables
2. DoE: *Latin Hyper Cube*
3. RSM: *Support Vector Machine*
4. Optimizer: *Gradient based NLPQL*

Improved Turbine Design



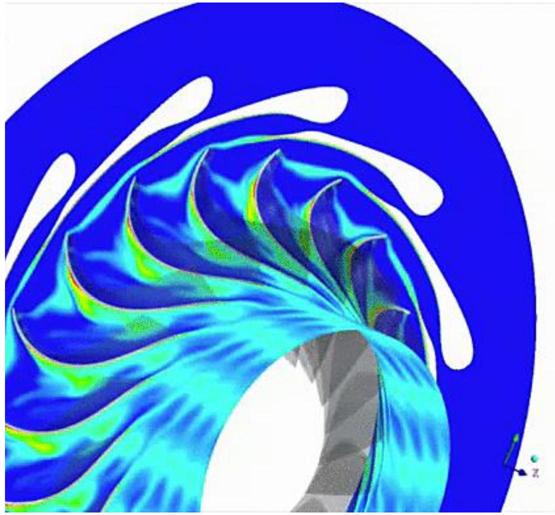
$\eta_{ts} = 84\%$



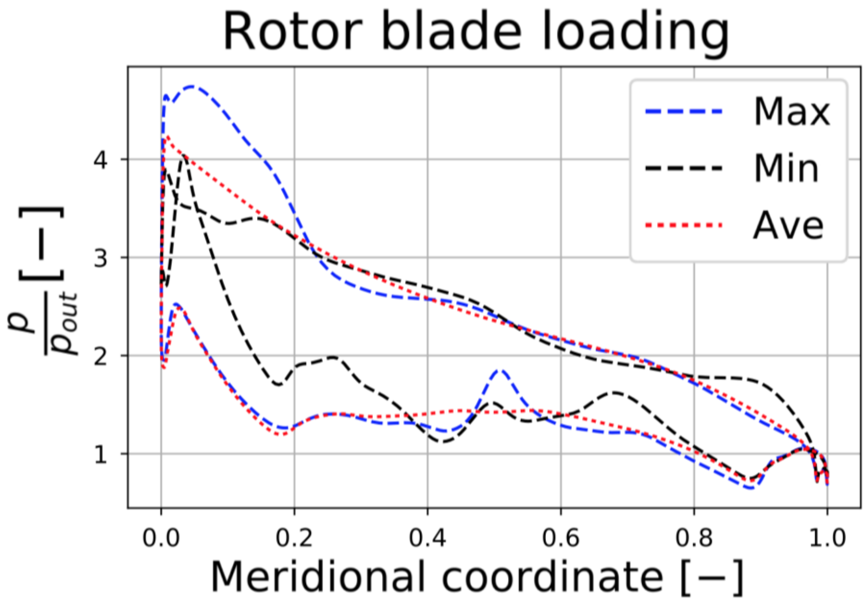
No longer flow separation → $\boldsymbol{\Delta\eta_{ts} = 2.4\%}$ → $\boldsymbol{\Delta\eta_{cycle} \sim 1\%}$

Unsteady Simulation

Stator-rotor Interaction



I. Impact on Performance



Unsteady Fluctuations		
	Min	Max
$Efficiency$	$\mathbf{-0.6\%}$	$\mathbf{+0.4\%}$
$Blade\ loading$	-11.0%	$+11.0\%$

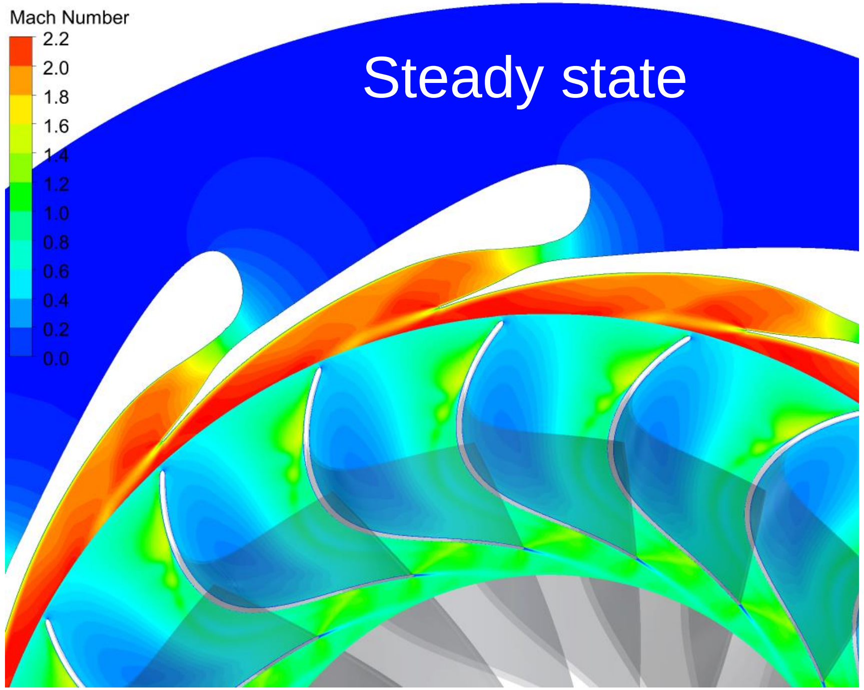
II. Aerodynamic loads about $^{1}/_{10}$ of centrifugal loads

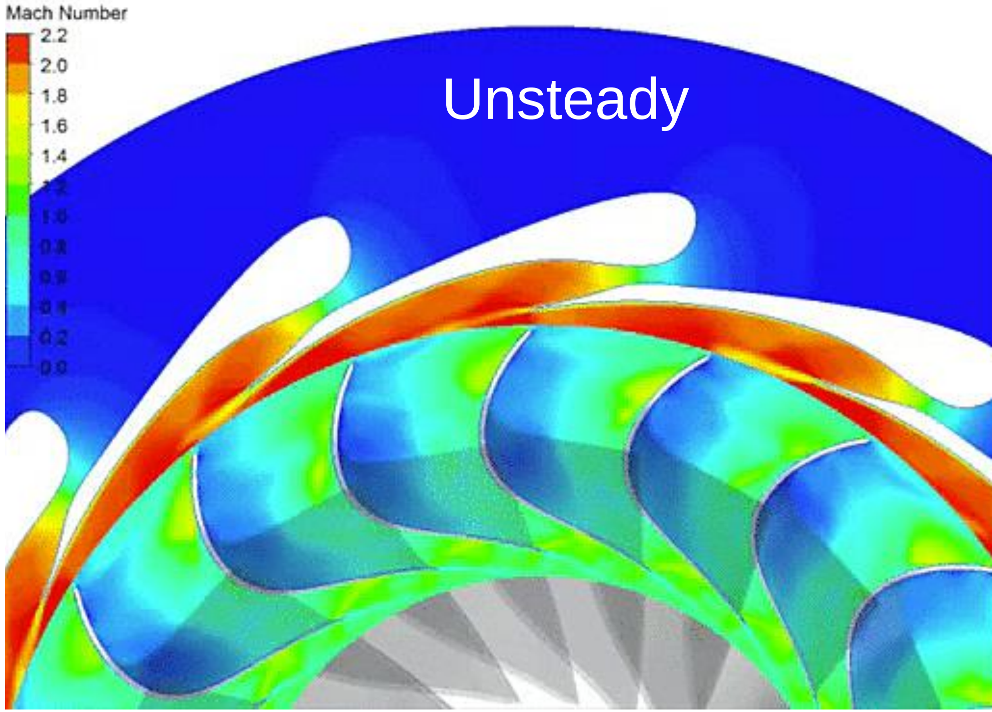
Small efficiency oscillation & No HCF induced by aerodynamic loads

Turbine simulation

Unsteady

III. Steady state vs. unsteady results





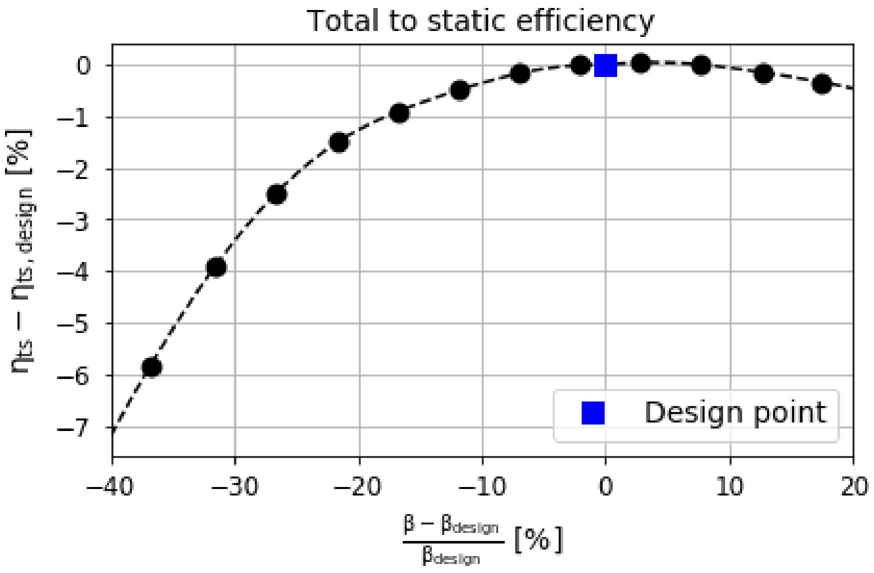
Mean flow features well represented by steady state

Off-Design Performance

Characteristic Curve

1. Constant: $\omega - p_{\text{out}} - T_{\text{t,in}}$
2. Changing: $p_{\text{in}}\ (\dot{m})$

Off-design performance			
		Min	Max
$Power$:	P/P_{des}	50%	120%
$Efficiency$:	$\eta - \eta_{des}$	-6.0%	-0.3%



High efficiency for a relatively wide range of expansion ratio

Key Take-Aways

I. Highly efficient mini-RIT elaborating high Vol flow ratio **is feasible**

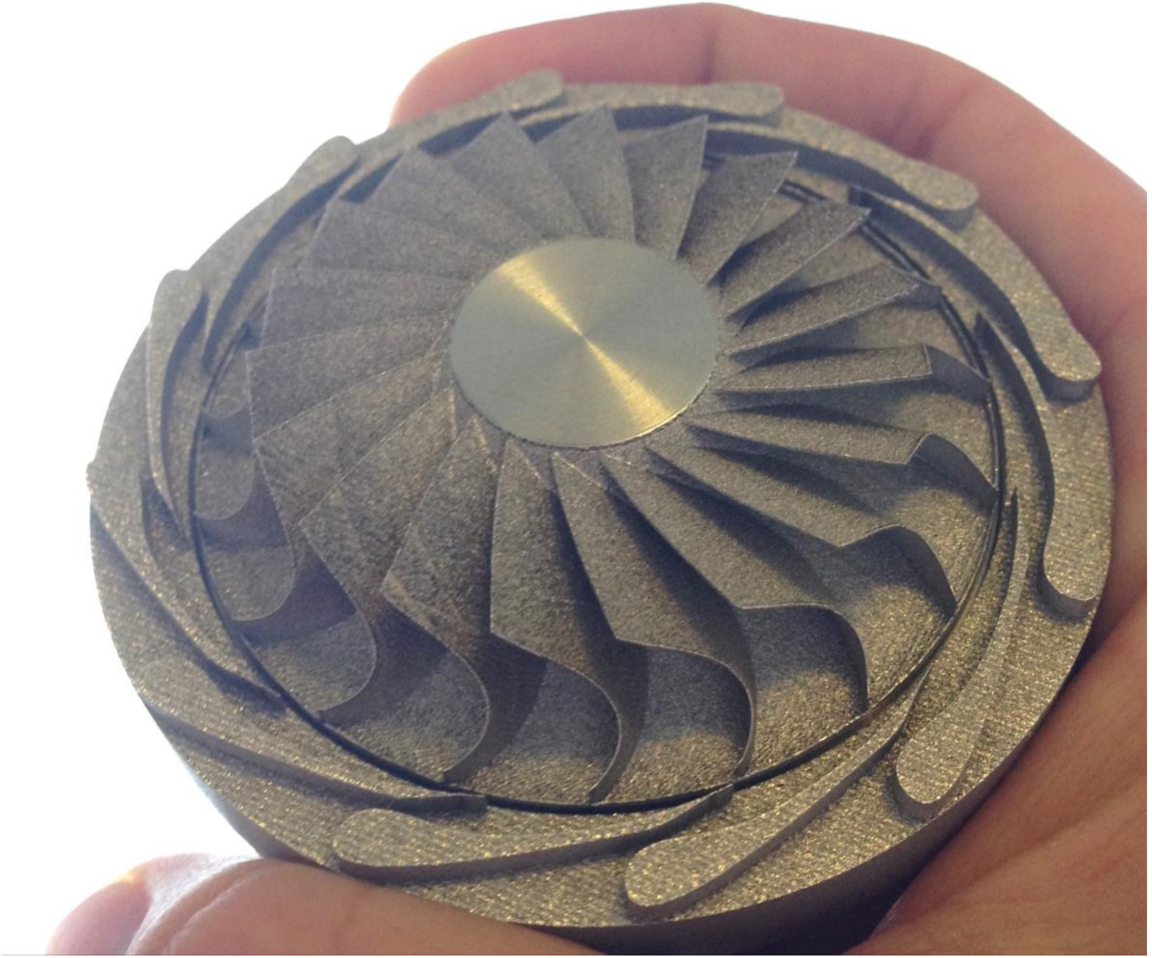
II. Turbochargers **design guidelines** not applicable to mini-RIT

III. Significant efficiency gains by using **CFD-based automated design**

IV. **Unsteady** simulation arguably not needed for global performance assessment

V. **Off-design** performance (more than) acceptable at partial loads

Let’s make it by AM!



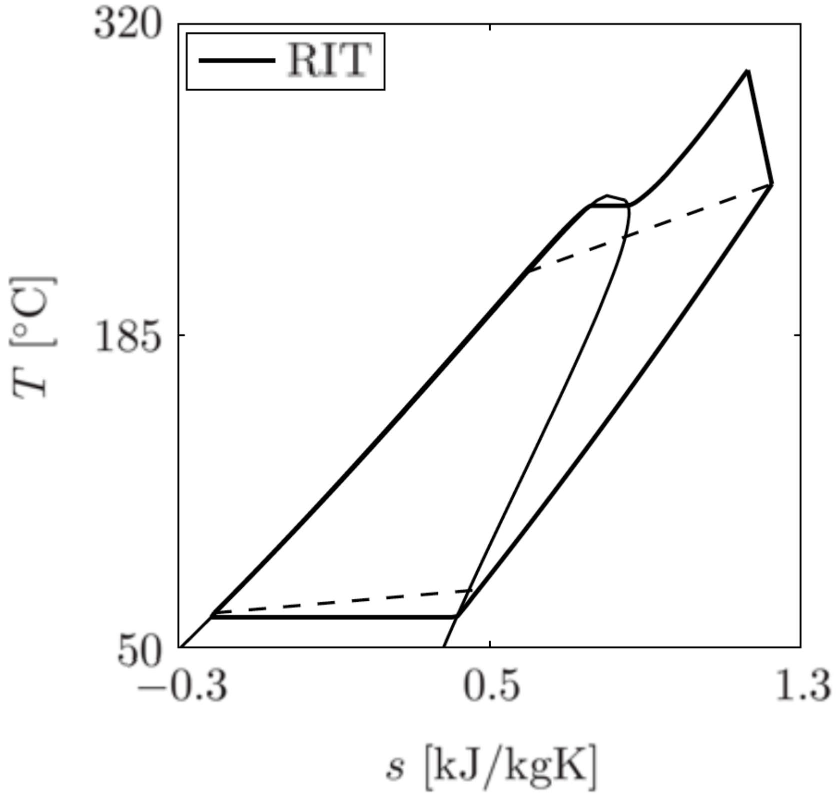
Thank You!

Turbine design

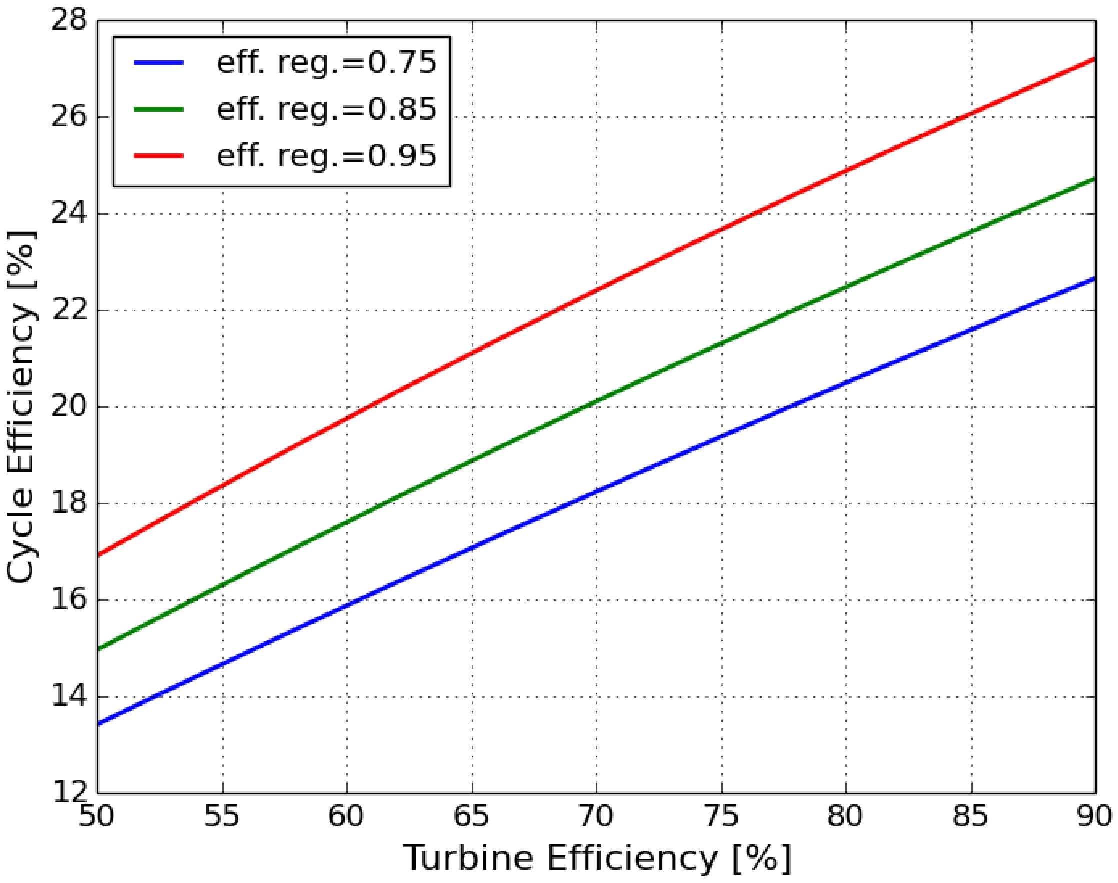
Preliminary design: zTurbo

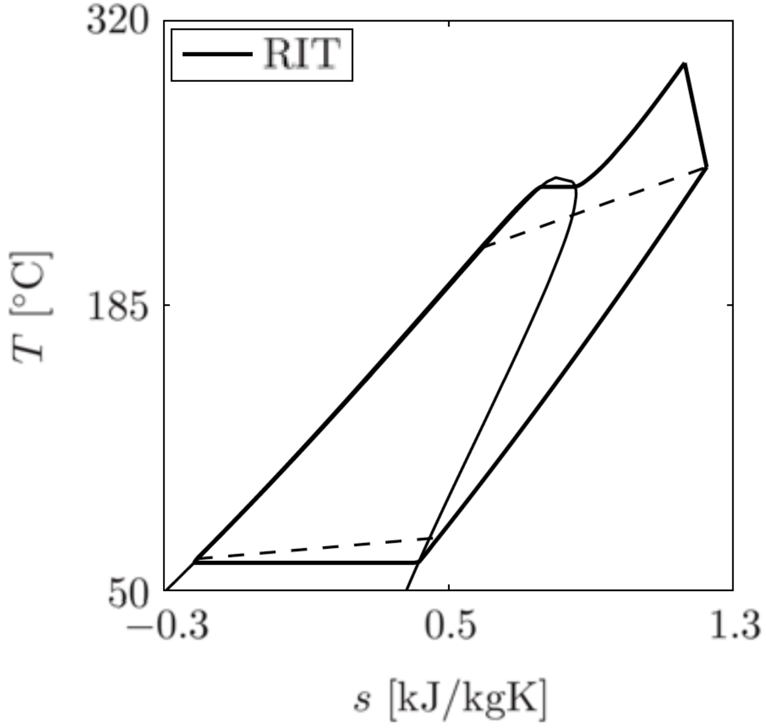
Turbine characteristics	
η_{ts}	83 %
n	98 $krpm$
p_{in}/p_{out}	40
$Working\ fluid$	MM

Boundary conditions	
p_{in}	18.1 bar
T_{in}	300 °C
p_{out}	0.4 bar



Turbine efficiency pays out



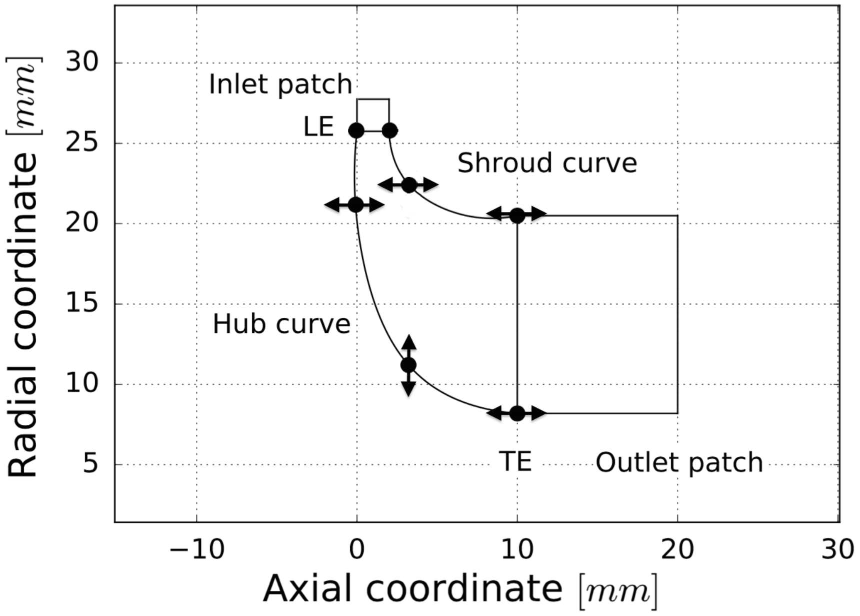


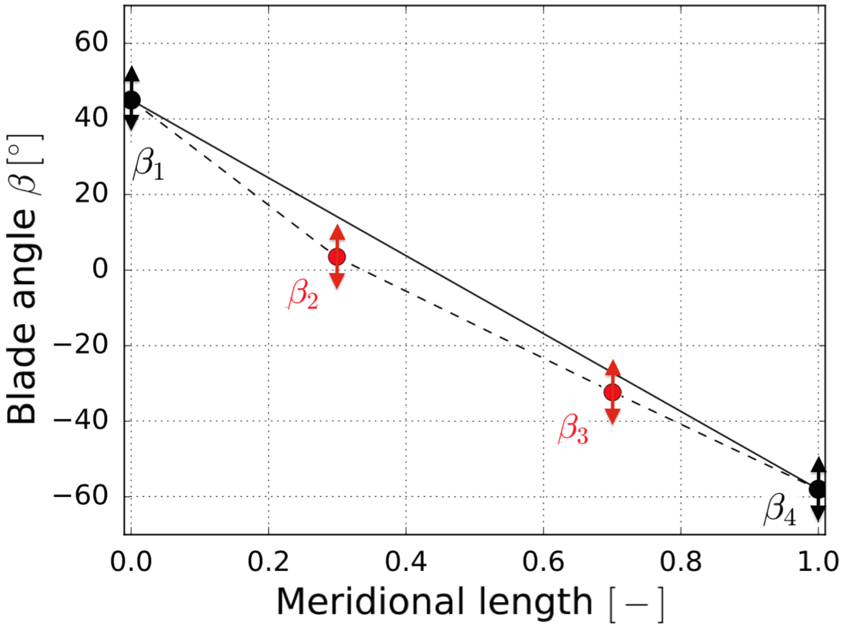
Turbine design

3D Geometry

- Stator MoC

- Rotor parametrized geometry



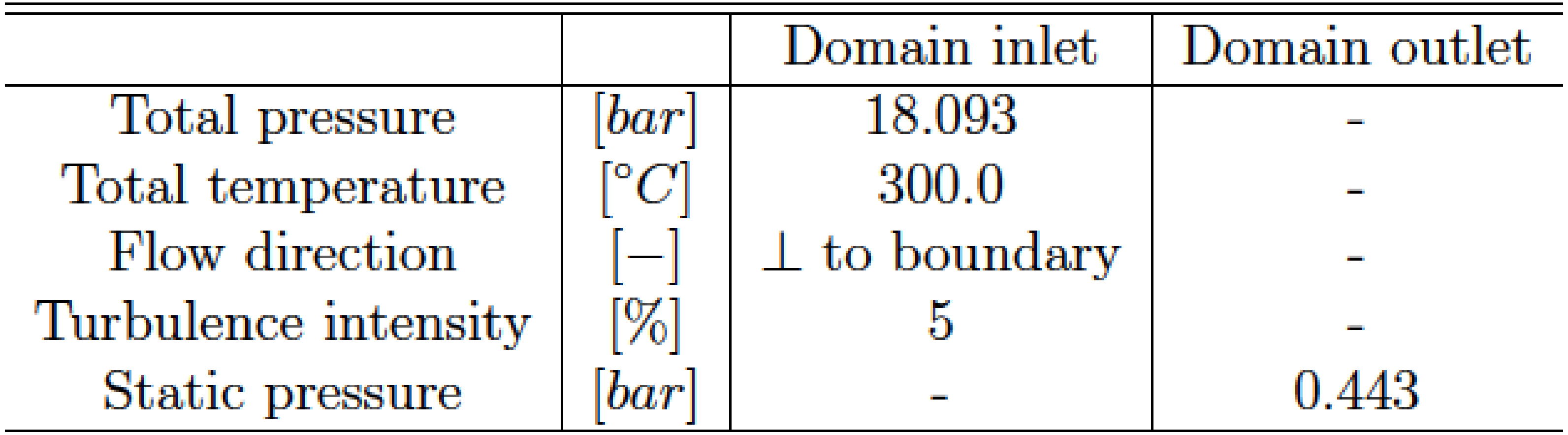


Technical approach

- 3D steady-state and unsteady fully turbulent (Ansys-CFX)
- SST-kω turbulence model without wall functions ($y^+ \approx 1$)
- Look-up tables for thermo-physical properties
- Ansys Workbench for shape optimization

Turbine simulation

Boundary conditions

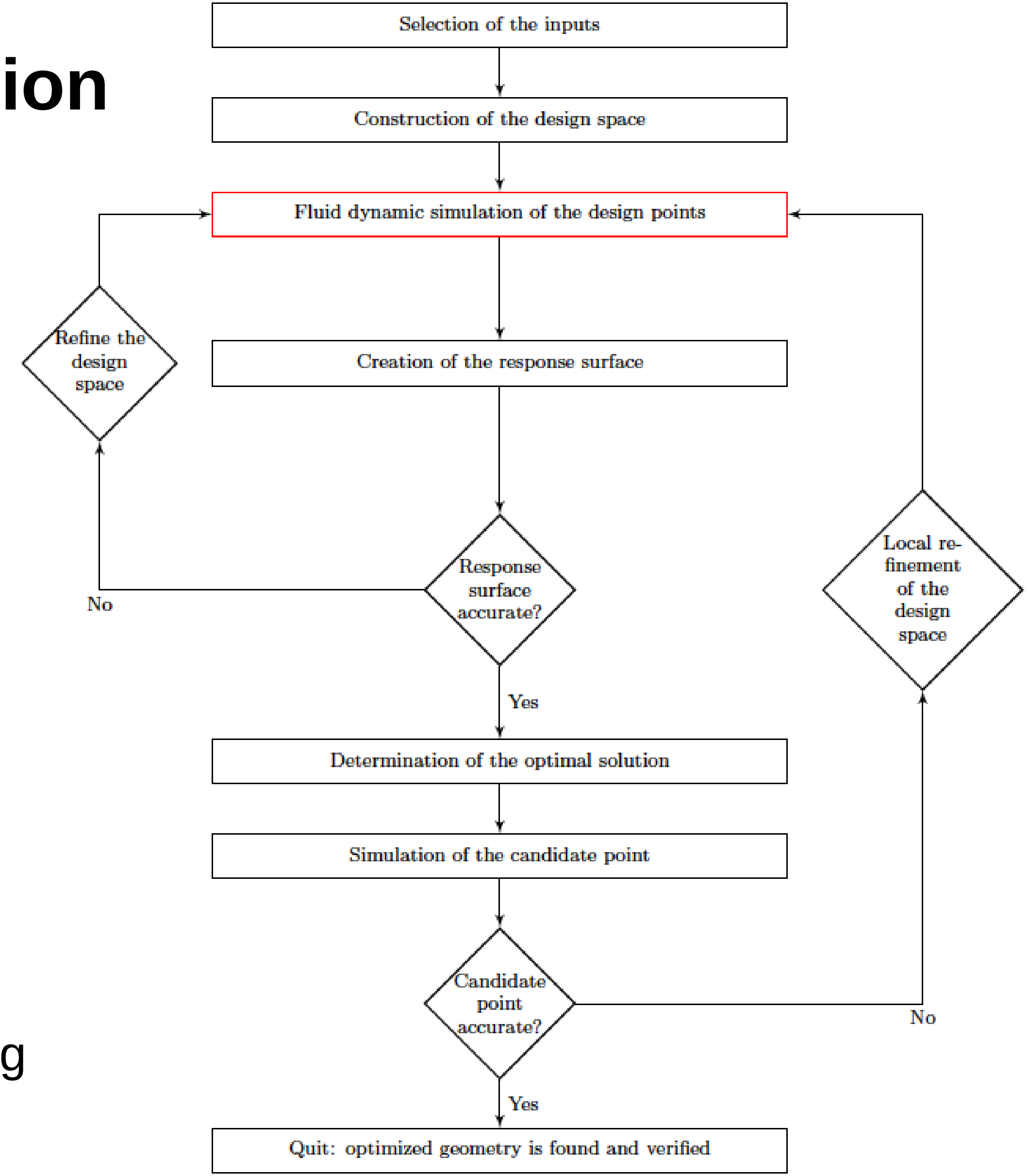


		Domain inlet	Domain outlet
Total pressure	$[bar]$	18.093	-
Total temperature	$[^\circ C]$	300.0	-
Flow direction	$[-]$	$\perp$ to boundary	-
Turbulence intensity	$[\%]$	5	-
Static pressure	$[bar]$	-	0.443

Turbine design

CFD-based shape optimization

- Selection of the inputs
- Design space sampling:
  - Latin Hyper Cube
- Fluid dynamic simulation of the DPs
- Creation of the response surface
  - Support Vector Machine
- Determination of the optimal solution
  - Gradient based NLPQL and screening



Selection of the inputs

Construction of the design space

Fluid dynamic simulation of the design points

Creation of the response surface

Response surface accurate?

No

Refine the design space

Yes

Determination of the optimal solution

Simulation of the candidate point

Candidate point accurate?

No

Local refinement of the design space

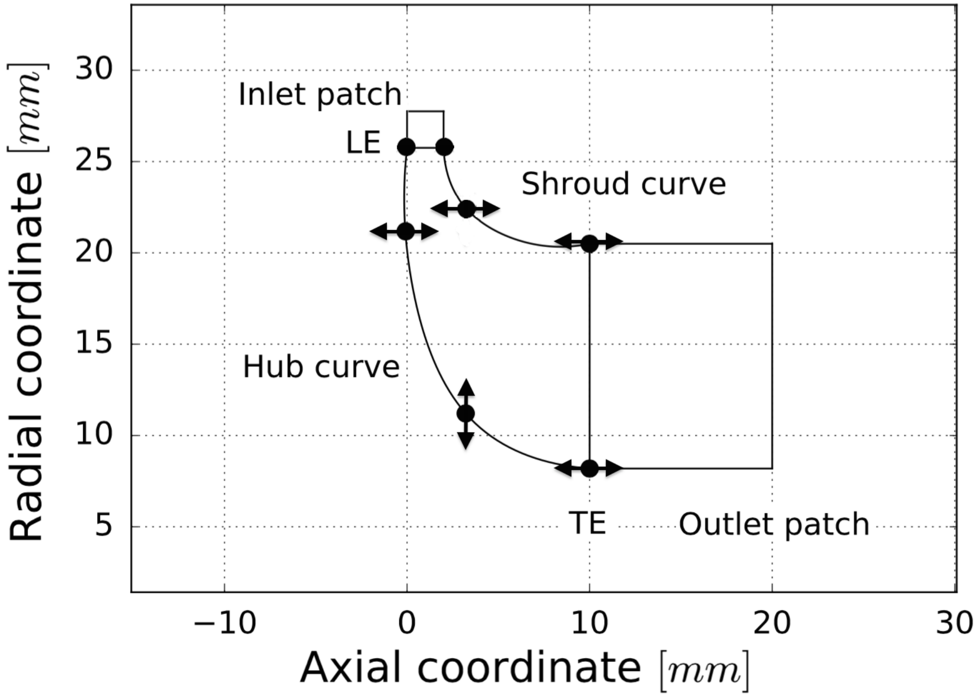
Yes

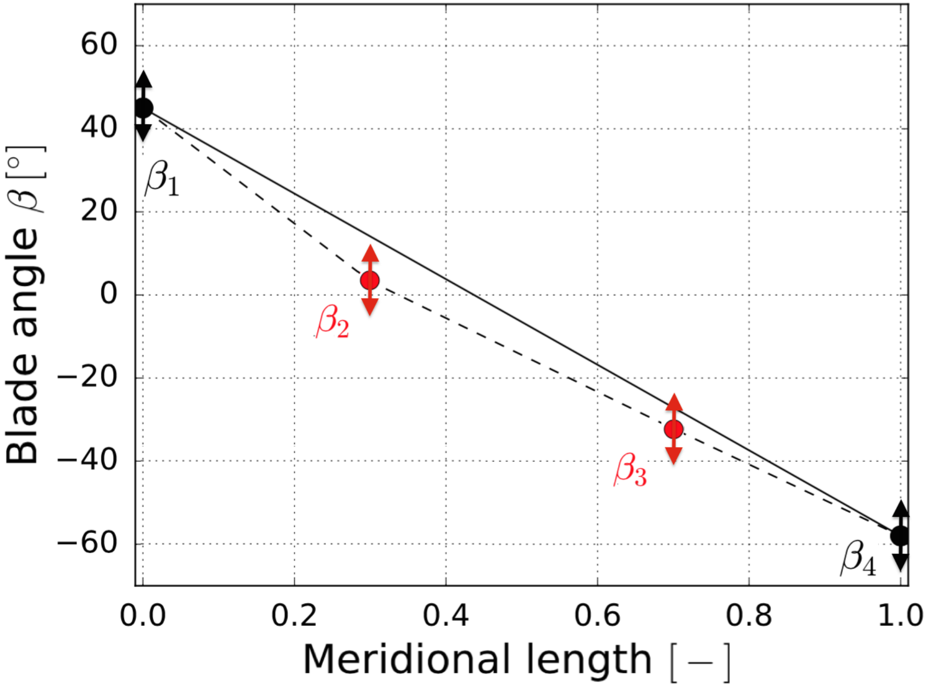
Quit: optimized geometry is found and verified

Turbine design

CFD-based shape optimization: 13 design variables

Blade number:	1 DoF	Blade curvature:	4 DoF
Meridional channel:	5 DoF	Blade angle:	3 DoF





Turbine design

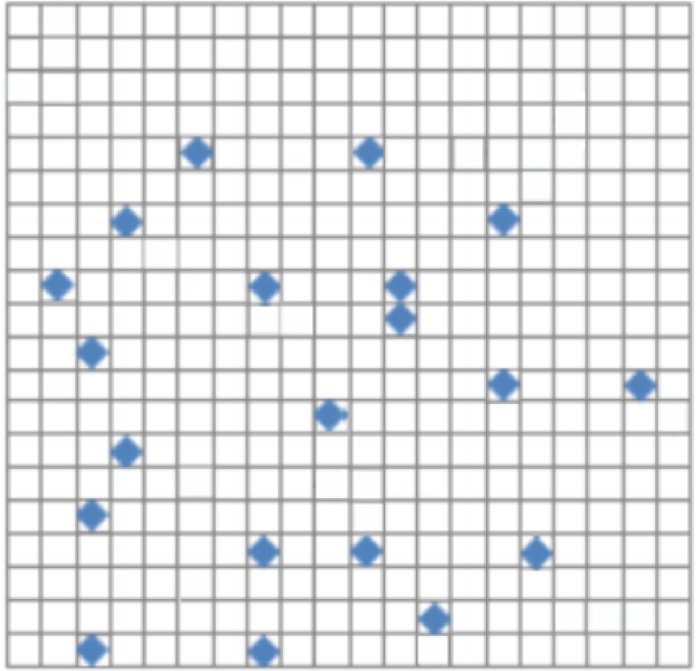
CFD-based shape optimization: 3 subsequent problems

1. Optimization of the **meridional channel** shape
    - 55 design points
2. Optimization of the **blade curvature**
    - 44 design points
3. Optimization of the **blade angle** and **flow deflection**
    - 44 design points

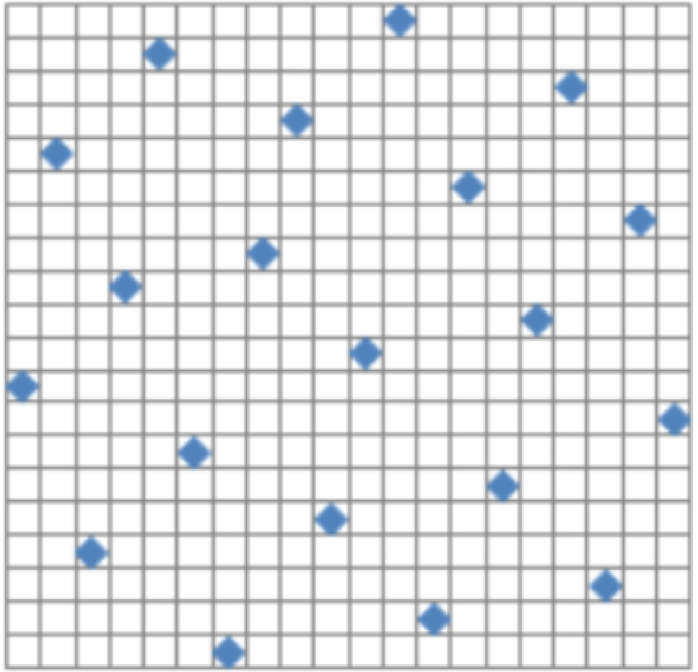
Turbine design

CFD-based shape optimization: design of experiment

Monte Carlo sampling



Latin Hypercube sampling



- 2 inputs
- 20 design points

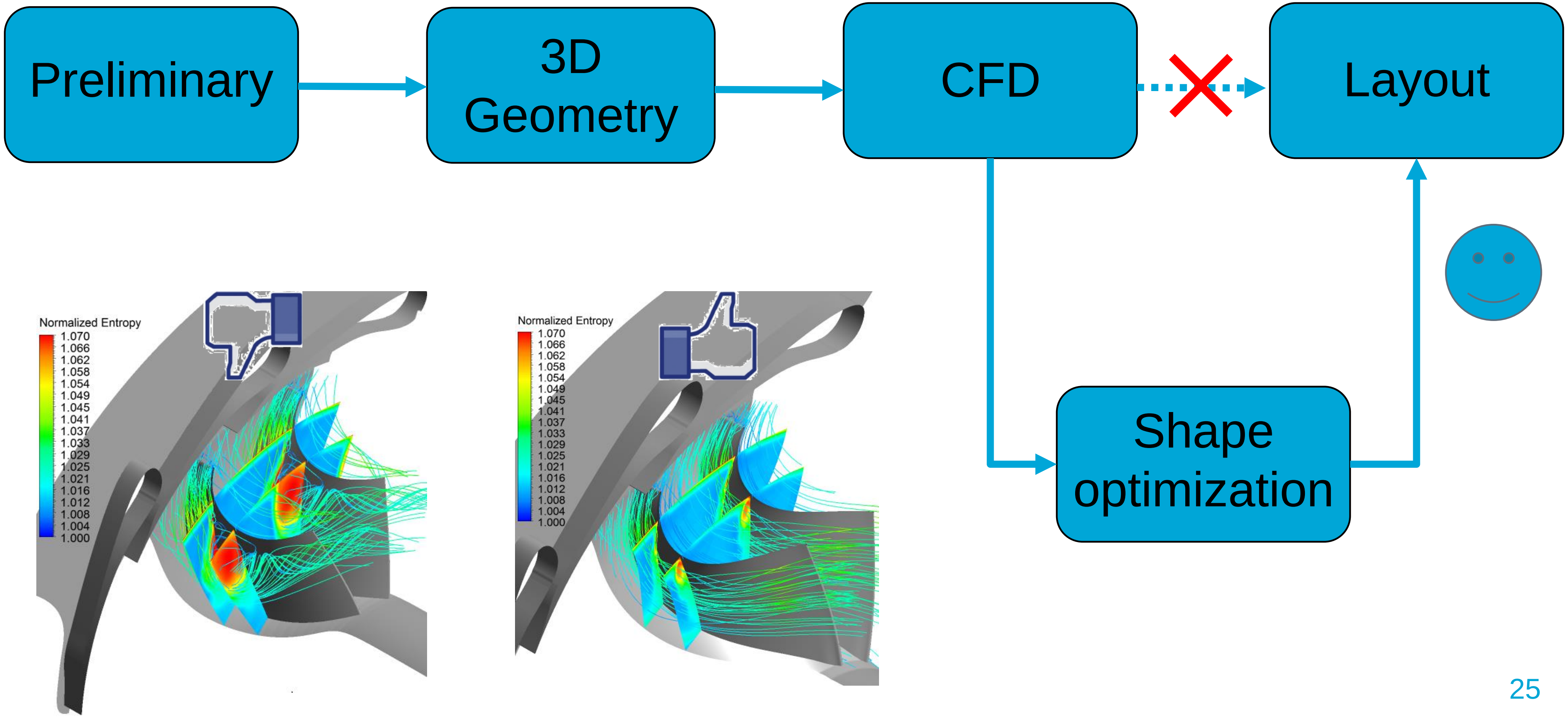
Turbine design

CFD-based shape optimization: overall parameters

- Number of **degrees of freedom:** *13*
- Number of **design points:** *143*
- **Objective function:** *total to static efficiency*

- **Design of Experiment:** *Latin Hypercube*
- **Response surface:** *Support Vector Machine*
- **Objective function:** *Screening or gradient based NLPQL*

Turbine design



Preliminary

3D Geometry

CFD

Layout

Shape optimization

Turbine design

Baseline & Optimized: losses breakdown

Loss	Location	
Profile:	In → TE	midspan, free slip endwall, no tip clearance
Mixing:	TE → Out	midspan, free slip endwall, no tip clearance
Secondary:	In → Out	no tip clearance
Tip leakage:	In → Out	tip clearance
Kinetic energy:	Out	tip clearance

$$\Delta\eta_{ts} = \frac{\Delta h_{loss}}{\Delta h_{is}}$$

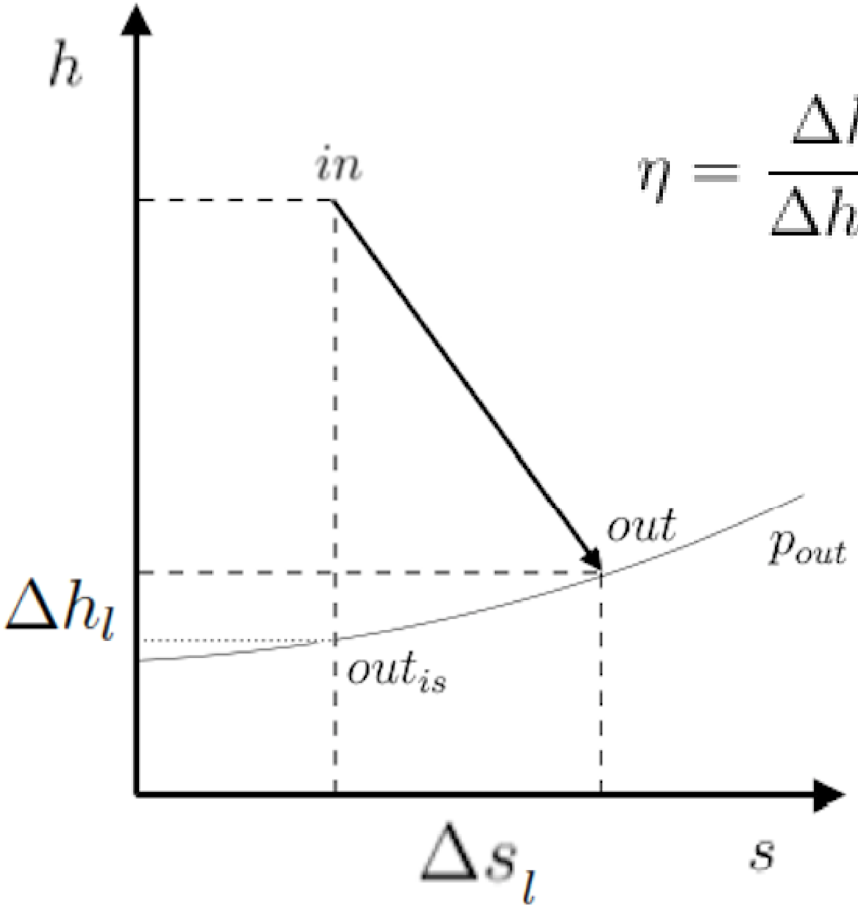
Turbine design

Baseline & Optimized: losses breakdown

- Profile loss: $\Delta s_p = \left(s_{TE} - s_{in}\right)_{midspan,\, free\, slip\, endwall,\, no\, tip\, clearance}$
- Mixing loss: $\Delta s_{mix} = \left(s_{out} - s_{TE}\right)_{midspan,\, free\, slip\, endwall,\, no\, tip\, clearance}$
- Secondary loss: $\Delta s_{sec} = \left(s_{out} - s_{in}\right)_{no\, clearance} - \Delta s_{mix} - \Delta s_p$
- Tip leakage loss: $\Delta s_c = \left(s_{out} - s_{in}\right)_{tip\, clearance} - \Delta s_{sec} - \Delta s_{mix} - \Delta s_p$
- Kinetic energy loss: $\Delta h_{TE} = \left(h_{t,\, out} - h_{out}\right)_{tip\, clearance}$

Turbine design

Baseline & Optimized: losses breakdown

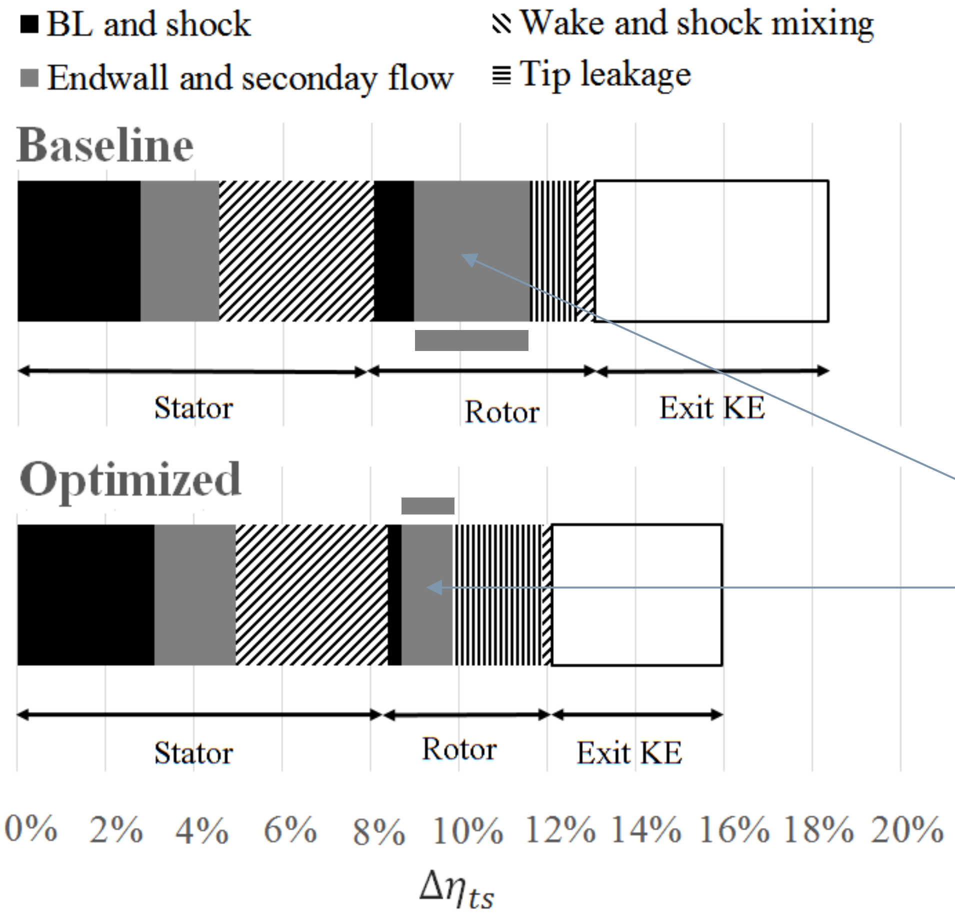


$$\eta = \frac{\Delta h}{\Delta h_{is}} = \frac{\Delta h_{is} - \Delta h_l}{\Delta h_{is}} = 1 - \frac{\Delta h_l}{\Delta h_{is}}$$

$$T\,ds = dh - v\,dp$$

Turbine design

Baseline & Optimized: losses breakdown



$$\eta_{ts,\,optimized} - \eta_{ts,\,baseline} = 2.4\ \%$$

Stator losses:

- Different reaction degree

Rotor losses:

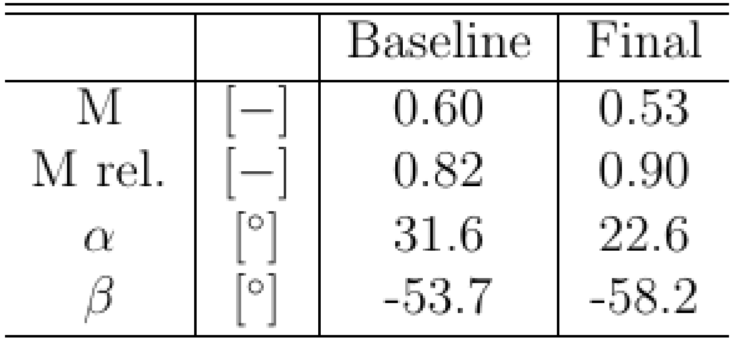
- Endwall and secondary flow ↓
- Exit kinetic energy ↓

Turbine design

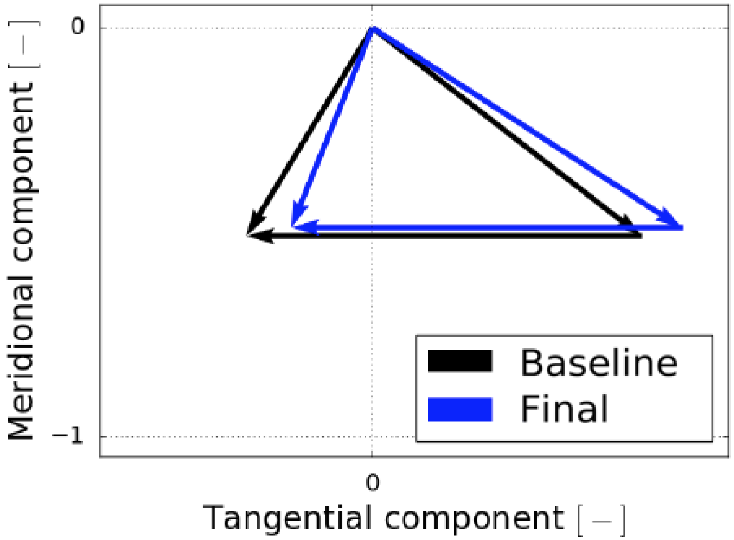
Baseline & Optimized: losses breakdown

Lower KE loss for final geometry

- Streamlines attached to the blade:
  - *Higher relative Mach*
  - *Lower absolute Mach*

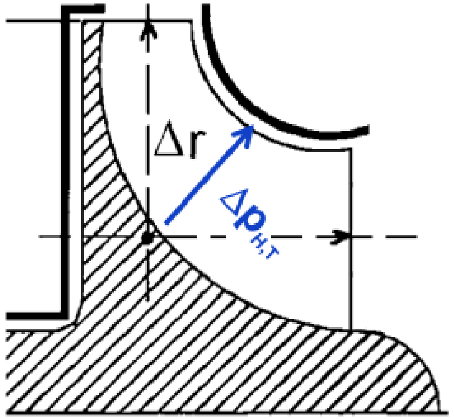


		Baseline	Final
M	[–]	0.60	0.53
M rel.	[–]	0.82	0.90
α	[°]	31.6	22.6
β	[°]	-53.7	-58.2

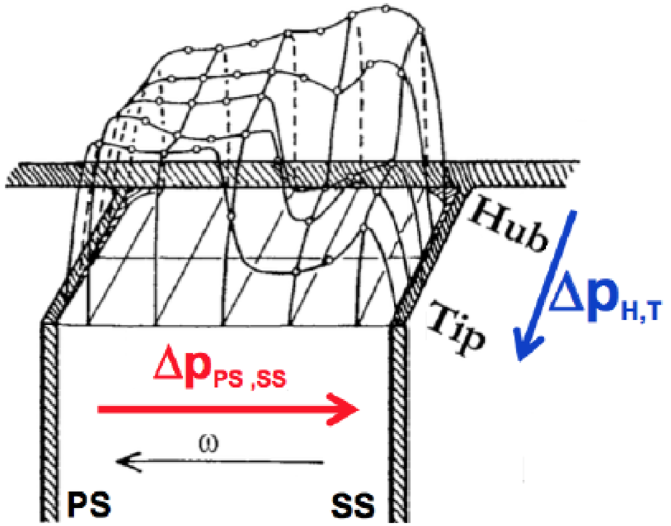


Turbine design

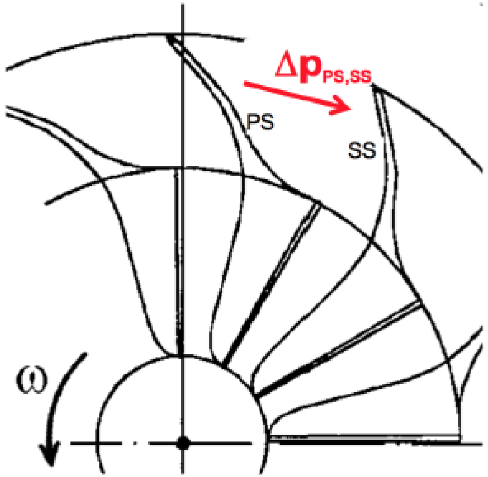
Baseline & Optimized: losses breakdown, secondary flow



(a) Rotor radial-to-axial bend pressure gradient.



(b) Rotor outlet flow field schematic.

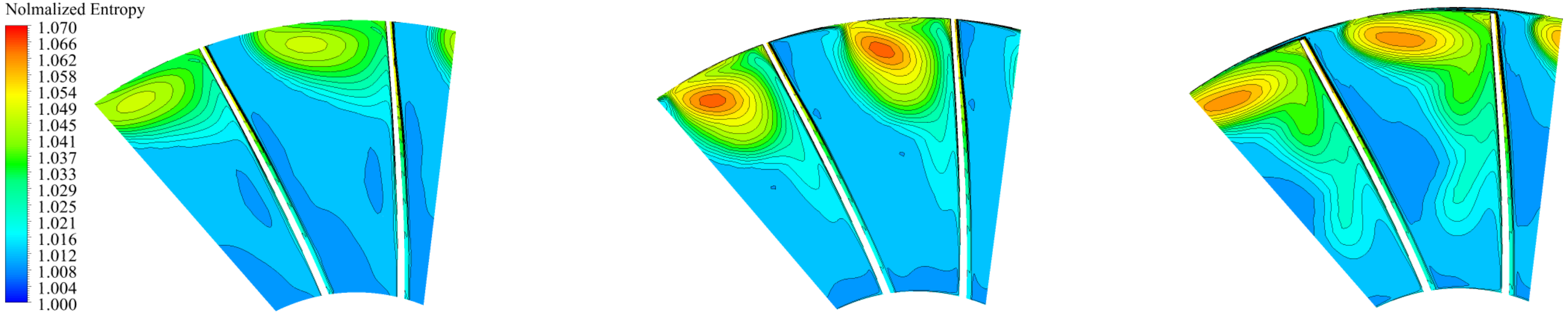


(c) Suction to pressure side pressure gradient.

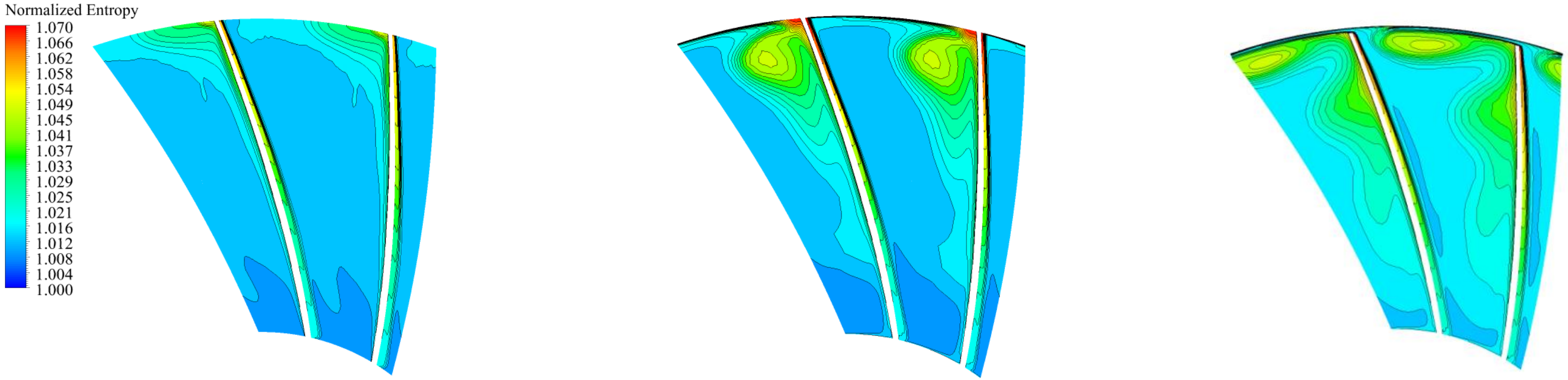
Turbine design

Baseline & Optimized: losses breakdown

Entropy at rotor outlet



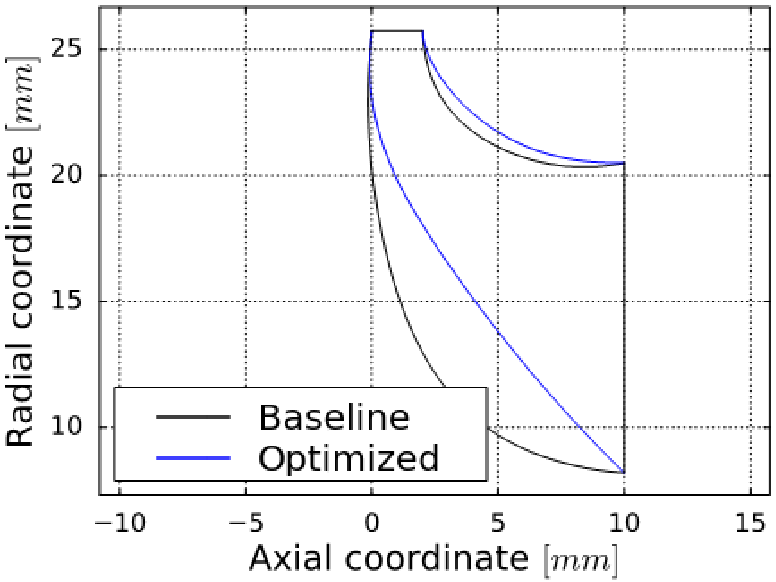
Endwall free slip No clearance Tip clearance

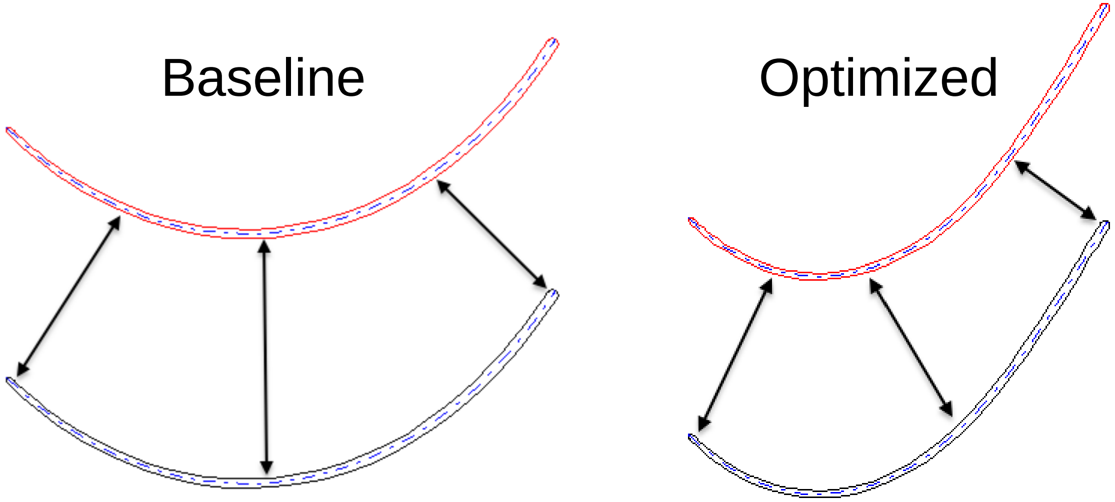


Turbine design

Baseline & Optimized: blade optimization

- Higher number of blades
- Sharper hub contour
- Purely convergent channel on blade to blade plane





Turbine simulation

Unsteady

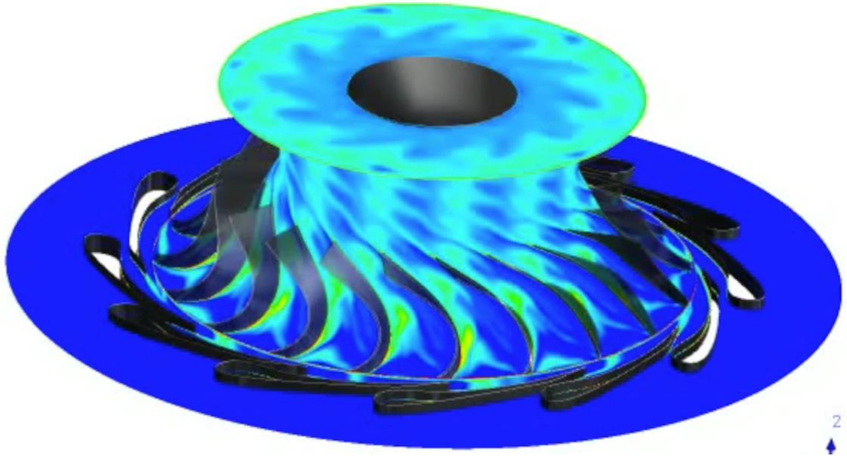
I. Unsteady effects magnitude

$$\tilde{\Phi} = \frac{\Phi_{max,min} - \Phi_{ave}}{\Phi_{ave}}$$

II. Blade loading variation in time

III. Steady state vs. unsteady results

$$\hat{\Phi} = \frac{\bar{\Phi}_{unsteady} - \Phi_{steady}}{\Phi_{steady}}$$

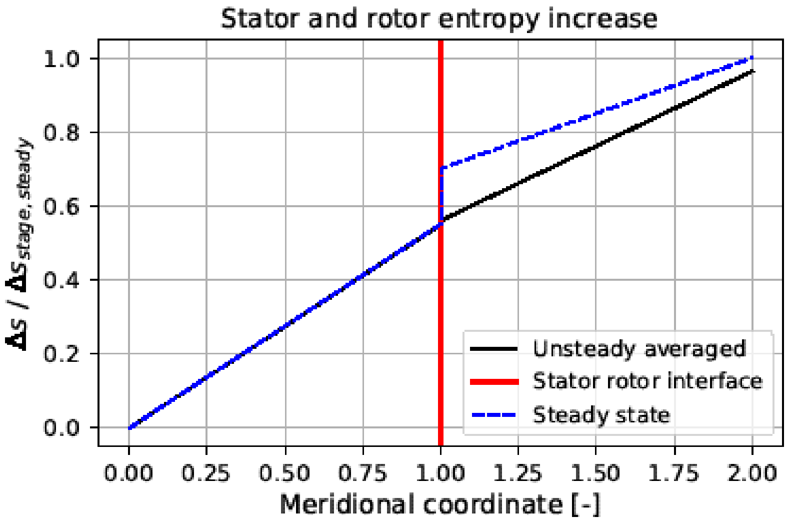


Turbine simulation

Unsteady

III. Steady state vs. unsteady results

Comparison index: unsteady vs. steady		
Efficiency	η_{ts}	+0.2%
Forces	*Stator*	+0.4%
	Rotor	+2.8%
Mach Numbers	*Stator outlet (abs)*	−0.2%
	Rotor inlet (rel)	+4.7%



Steady state simulation captures machine behavior for the present test case

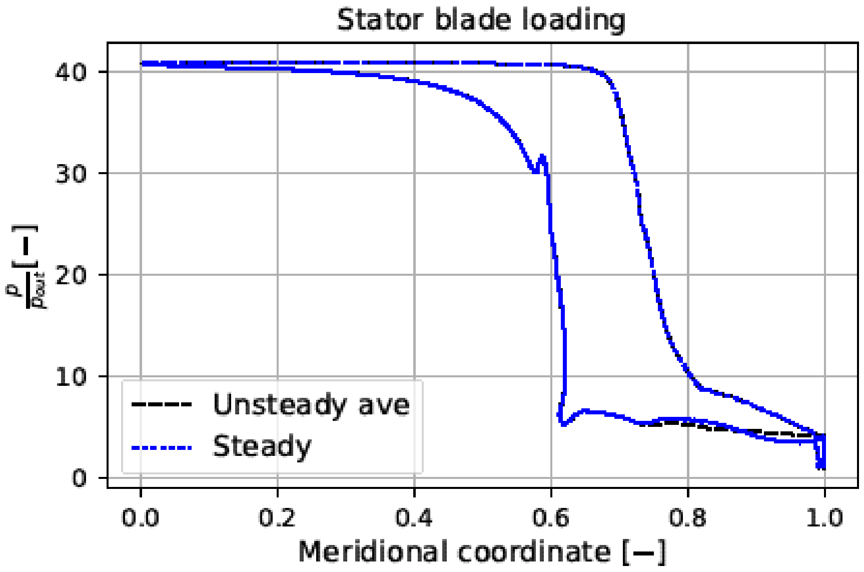
Turbine simulation

Unsteady

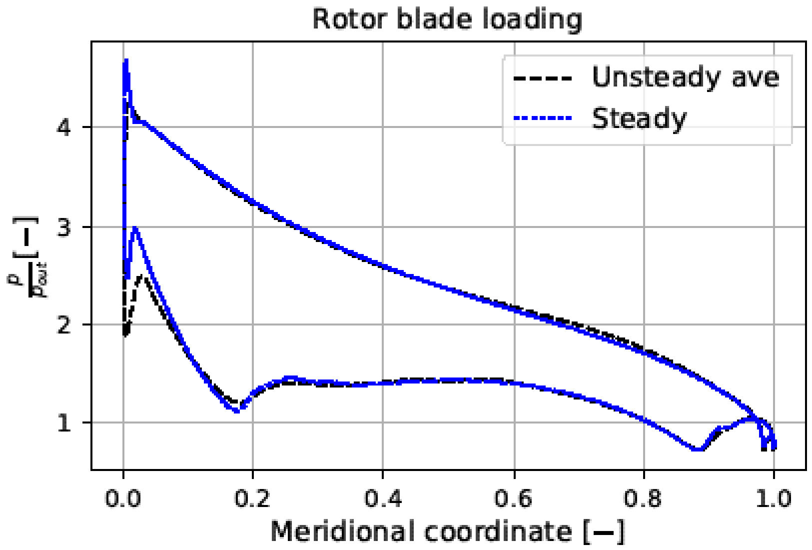
III. Steady state vs. unsteady results

Blade loading

Stator



Rotor



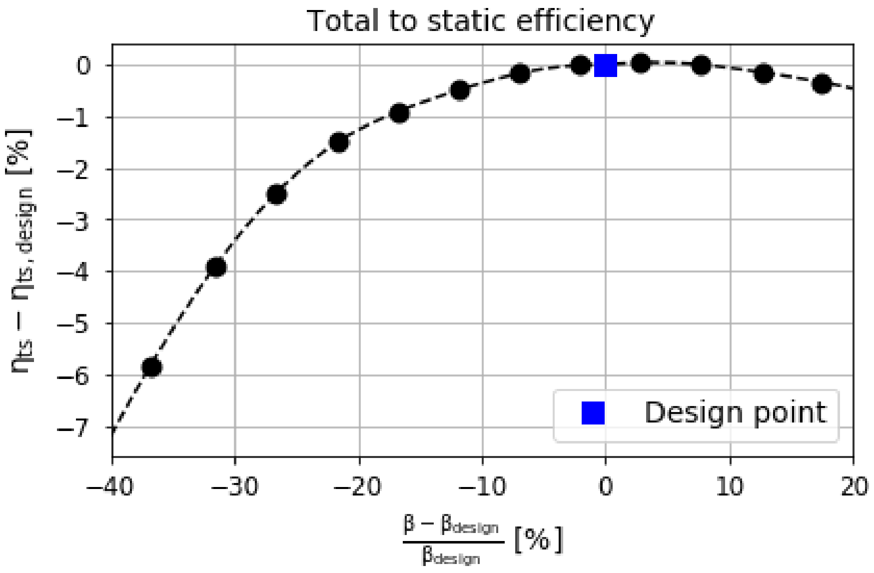
Blade loading well captured with steady state simulation

Turbine simulation

Off-design performance

1. Constant: $\omega - p_{out} - T_{t,in}$
2. Changing: $p_{in}\ (\dot{m})$

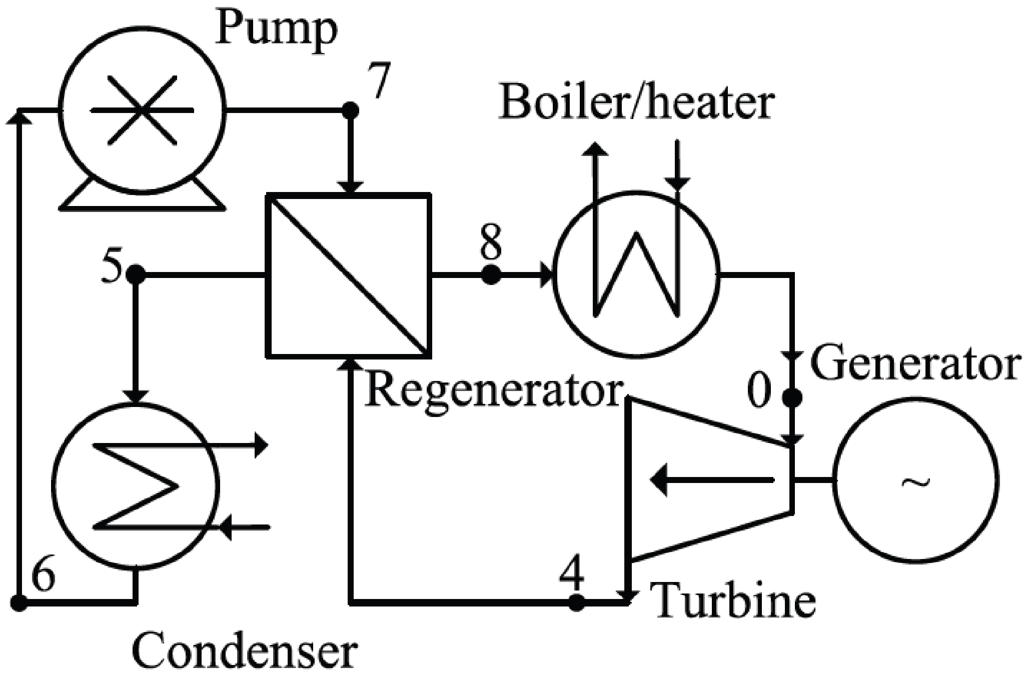
Off-design performance		
	Min	Max
$Expansion\ ratio$: β / β_{des}	63%	118%
$Mass\ flow$: $\dot{m} / \dot{m}_{des}$	62%	119%
$Power$: P / P_{des}	53%	120%
$Efficiency$: $\eta - \eta_{des}$	-5.9%	-0.3%

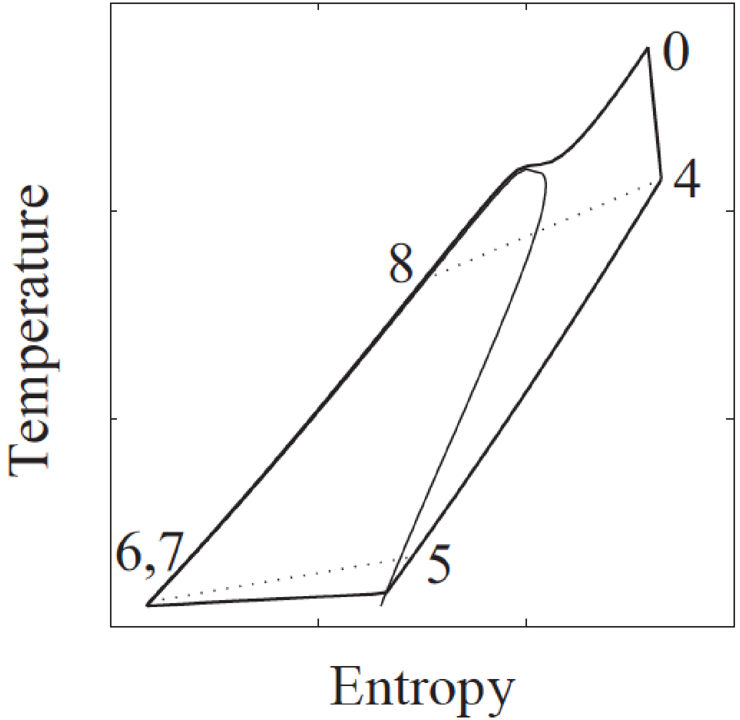


High efficiency for a wide range of mass flow variation

ORC system with regeneration

Process flow and temperature-entropy diagrams

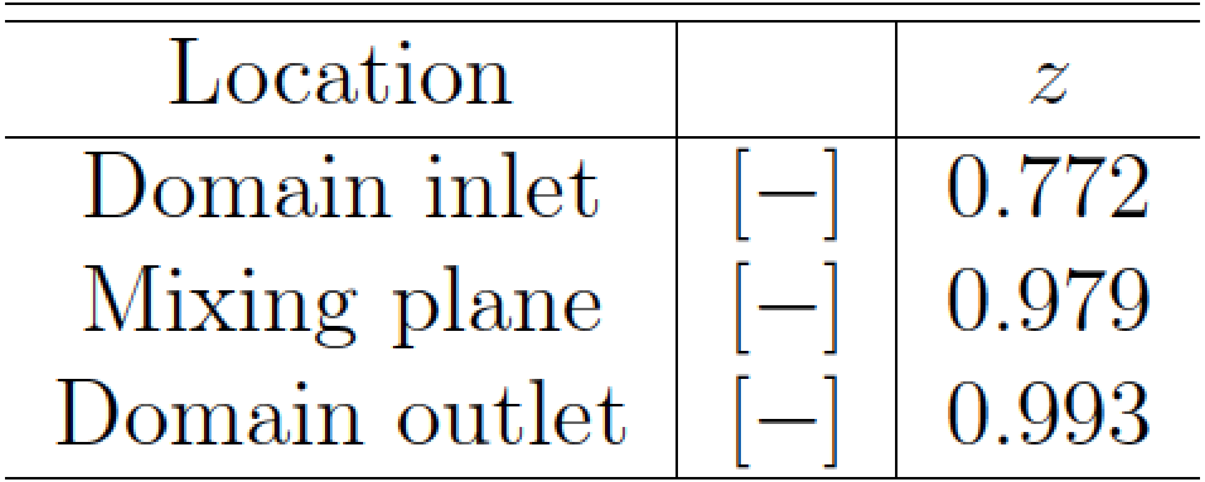




Turbine simulation

Fluid characterization, compressibility factor

- $z = \frac{V}{V_{id}} = \frac{p}{\rho \, R_{gas} \, T}$



Location		z
Domain inlet	$[-]$	0.772
Mixing plane	$[-]$	0.979
Domain outlet	$[-]$	0.993

Turbine design

Preliminary design: stator loss correlations

- Glassman profile loss: $$L_p = \frac{E\, k_s\, Re^{0.2}\, \frac{l_c}{s_{out}}}{\cos\alpha_{out} - \frac{t_{TE}}{s_{out}} - H\, k_s\, Re^{0.2}\, \frac{l_c}{s_{out}}}$$

- Glassman endwall loss: $$L_{end} = L_p\left(\frac{A_{3D}}{A_{2D}} - 1\right)$$

- Osnaghi mixing loss: $$L_{mix} = \frac{\left(1 + \frac{\gamma-1}{\gamma}\, M_a^2\right)^{\frac{\gamma}{\gamma-1}} - \frac{p_1}{p_a}\left(1 + \frac{\gamma-1}{\gamma}\, M_1^2\right)^{\frac{\gamma}{\gamma-1}}}{\left(1 + \frac{\gamma-1}{\gamma}\, M_a^2\right)^{\frac{\gamma}{\gamma-1}} - 1}\; \frac{V_{1-is}^2}{2}$$

TUDelft

Turbine design

Preliminary design: rotor loss correlations

- Baines profile loss: $$L_p = k_p \frac{L_H}{D_H} \frac{1}{2} \left(W_{in}^2 + W_{out}^2 \right)$$
- Baines endwall loss: $$L_{end} = k_p \left[0.68 \left[1 - \left(\frac{r_{out}}{r_{in}} \right)^2 \right] \frac{\cos \beta_{b-out}}{\frac{b_{out}}{\hat{c}}} \right] \frac{1}{2} \left(W_{in}^2 + W_{out}^2 \right)$$
- Baines tip leakage: $$L_c = \frac{U_{in}^3 N_b}{8 \pi} \left(K_z \epsilon_z C_z + K_r \epsilon_r C_r + K_{zr} \sqrt{\epsilon_z \epsilon_r C_z C_r} \right)$$

Turbine design

Additive manufacturing

- Printing time: 4 hours !
- Selective Laser Melting
- Stainless Steel 316
- Layer thickness 20 μm
- Surface roughness: Ra 7
- No support material
- Heat treatment: to reduce internal stress