4th European sCO_2 Conference 2021, March 23-24

NUMERICAL ANALYSIS OF A CENTRIFUGAL COMPRESSOR OPERATING WITH SUPERCRITICAL CO2

Renan Emre Karaefe[1], Pascal Post[1], Marwick Sembritzky[1], Andreas Schramm[1], Matthias Kunick[2], Uwe Gampe[3], Francesca di Mare[1]

[1]Ruhr Universität Bochum
Faculty of Mechanical Engineering
Chair of Thermal Turbomachines and Aeroengines
44801 Bochum, Germany

[2]Zittau/Goerlitz University of Applied Sciences
Faculty of Mechanical Engineering
Dept. of Energy Systems Technology
02763 Zittau, Germany

[3]Technische Universität Dresden
Faculty of Mechanical Science and Engineering
Chair of Thermal Power Machinery and Plants
01062 Dresden, Germany

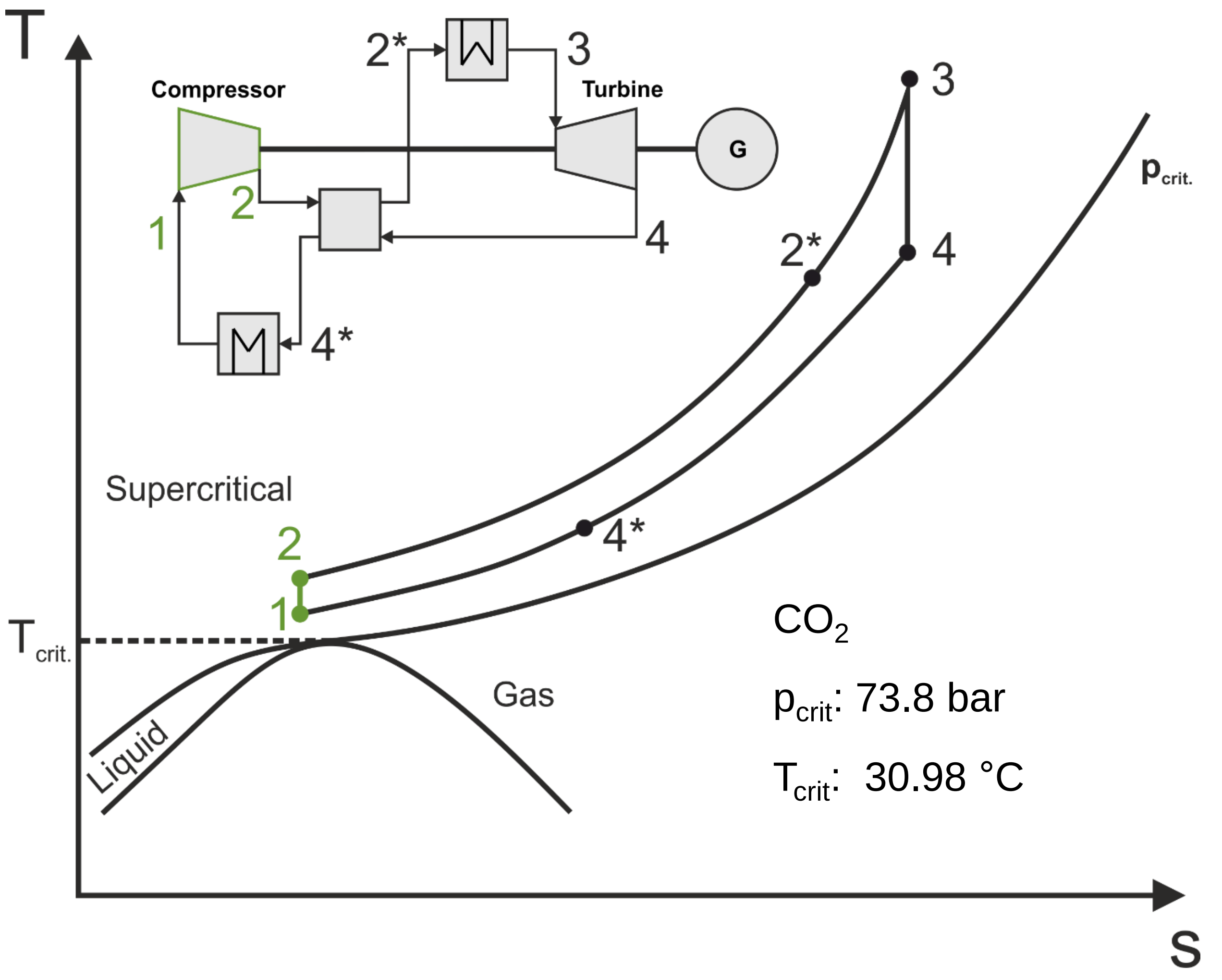
RUHR-UNIVERSITÄT BOCHUM
CHAIR OF THERMAL TURBOMACHINES AND AEROENGINES

Motivation

sCO_2-Power Systems

Characteristics

- Low compression work
- Small scale of turbomachinery
- Comparatively high efficiency in the mild turbine inlet temperature range (450 - 600°C)



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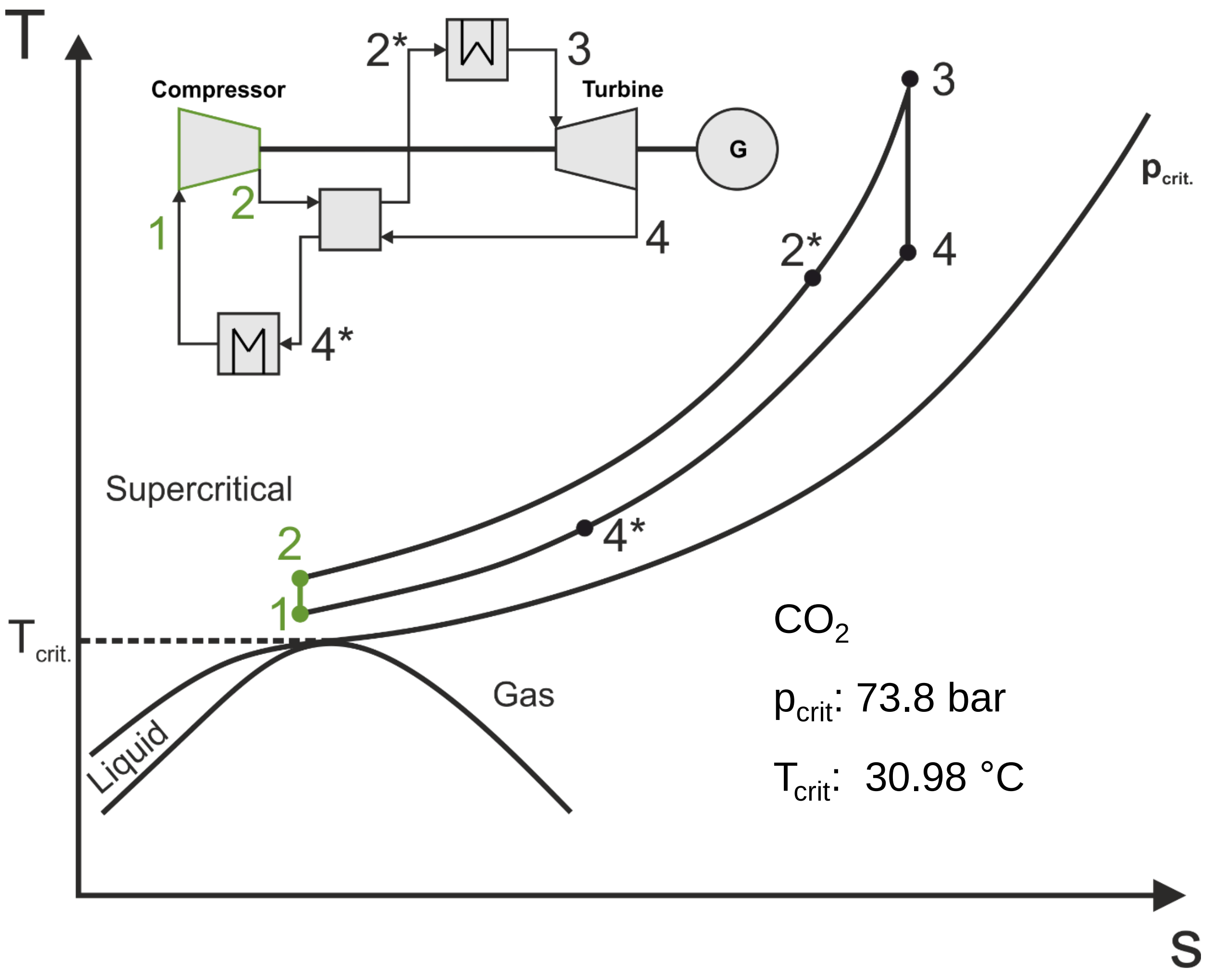
- Topping cycle for fossil fueled power plants
- Bottoming cycle for gas combined cycles
- Renewable energy
- Exhaust/waste heat recovery
- Nuclear energy



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TTF RUB

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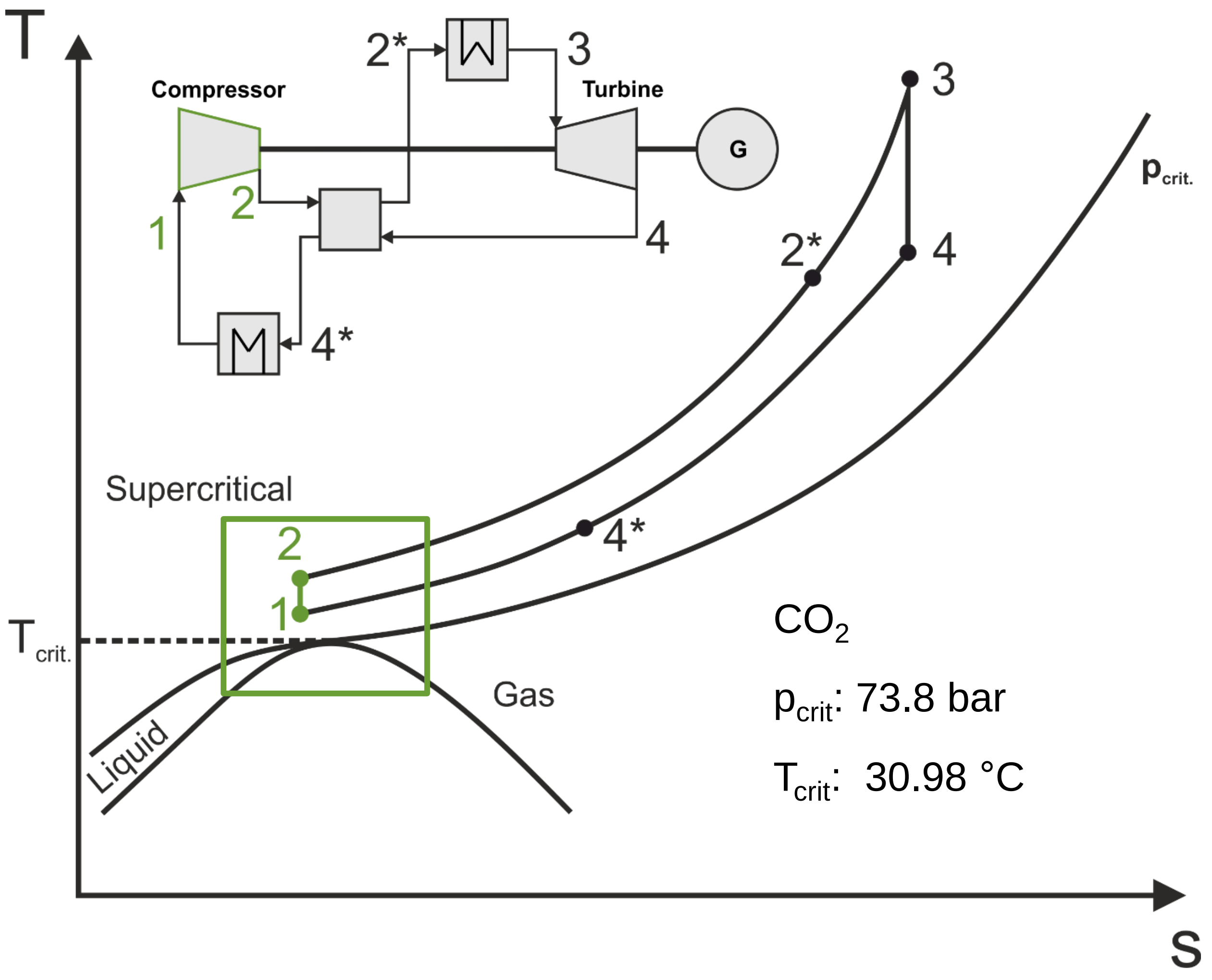
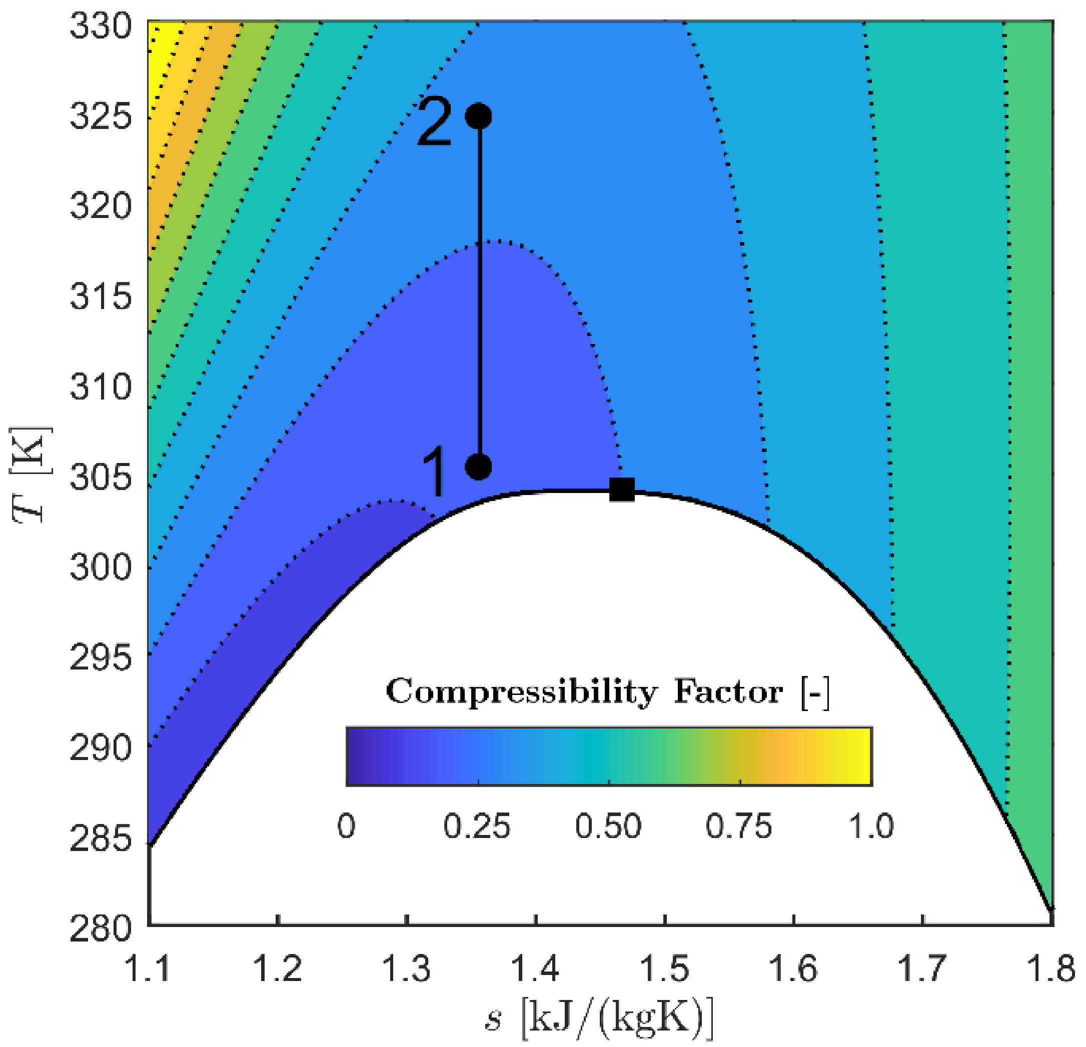


Challenges for Aerothermal Compressor Design and Analysis

- Non-ideal thermophysical properties



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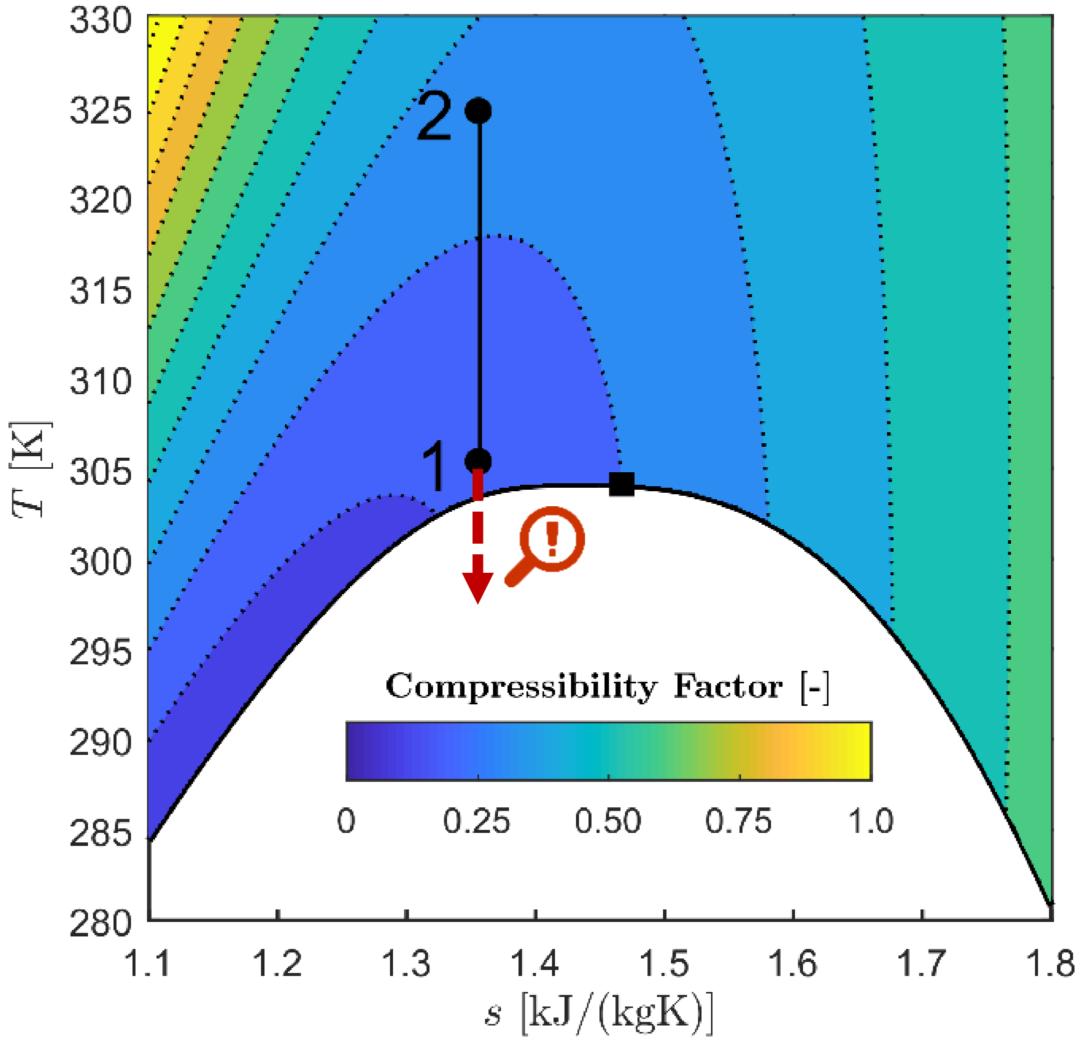
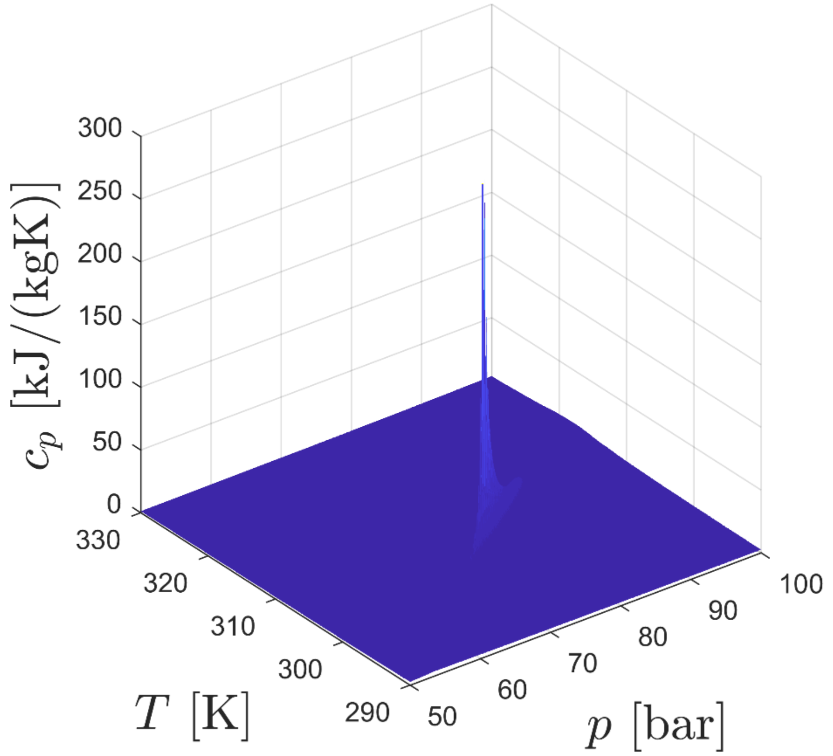
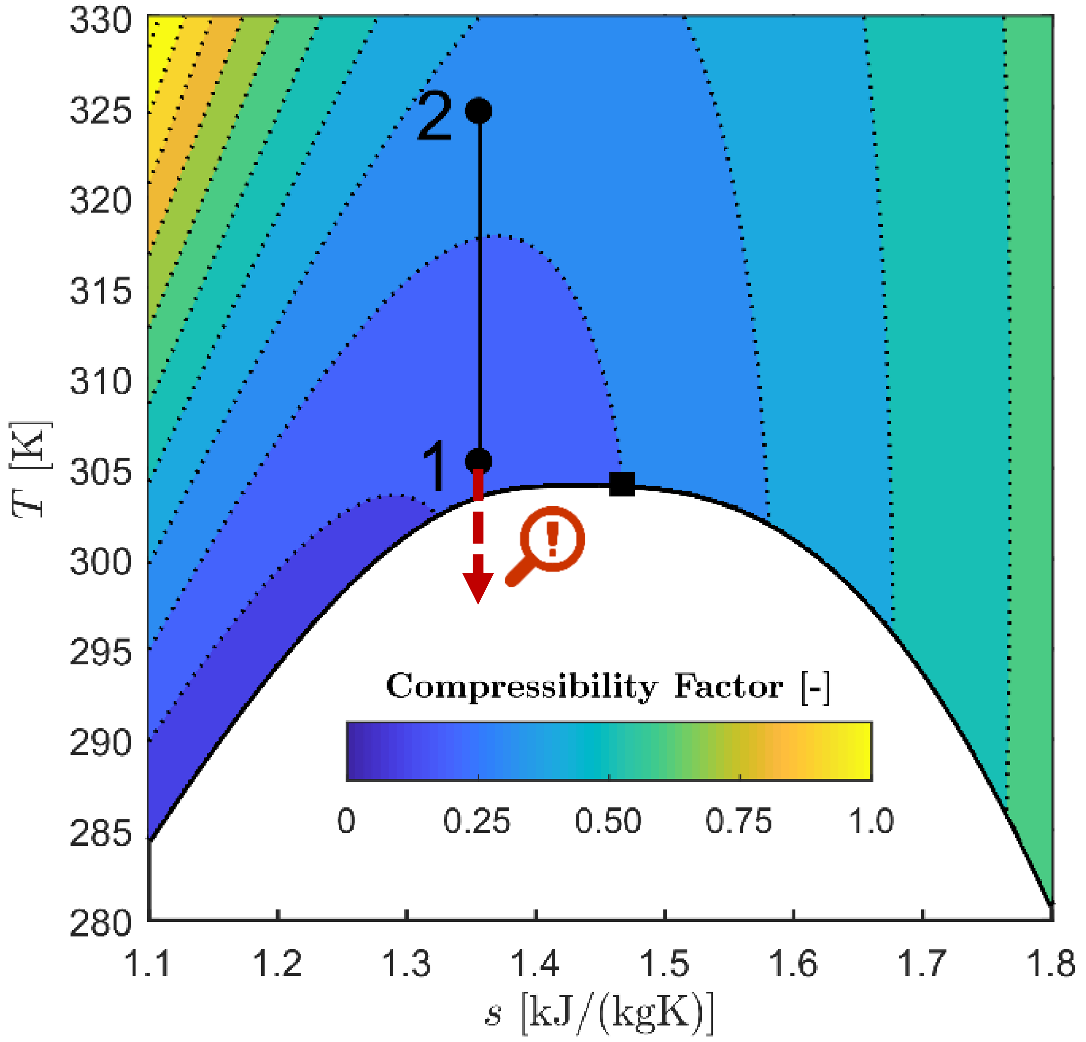


Challenges for Aerothermal Compressor Design and Analysis

- Non-ideal thermophysical properties
- Possibility of two-phase flows (locally)
- Rapidly changing fluid properties in the vicinity of the critical point





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- Extension of the in-house CFD solver to account for thermophysical properties of sCO_2 with high degree of accuracy and numerical stability

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  - Breakdown of individual loss contributions

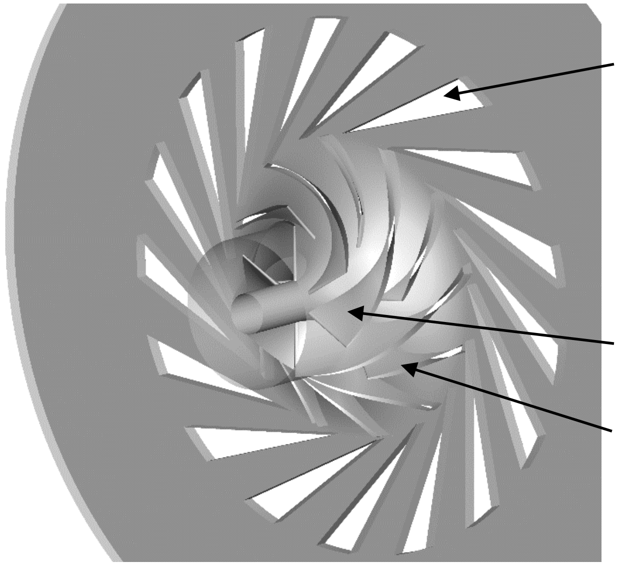
Outline

Test Case Description

SNL Compressor

- Candidate geometry based on main dimensions of the SNL compression test-loop main compressor
  - Backward swept impeller (50°), 6 main blades + 6 splitter blades
  - Channel diffuser, 17 vanes
  - Design specifications:
    50 kWe | 75 krpm | 3.54 $kg \cdot s^{-1}$ | $\eta_{ts} \approx$ 66% | π = 1,8
    $T_{0,in}/T_c \approx 1.004$ | $p_{0,in}/p_c \approx 1.04$ | $\rho_{0,in} \approx 576\ kg \cdot m^{-3}$

CAD model of the investigated stage geometry



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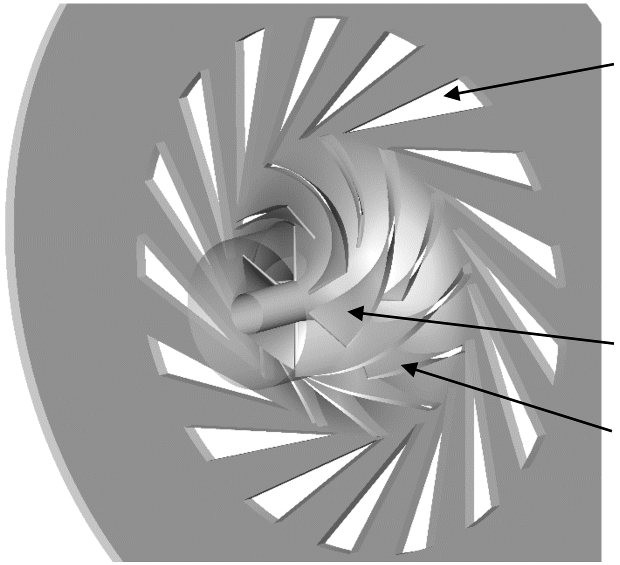

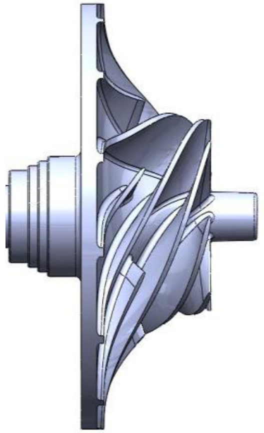

Part drawing and photograph of the SNL main compressor [4]

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- Simplifications
    - No tip clearance modeled

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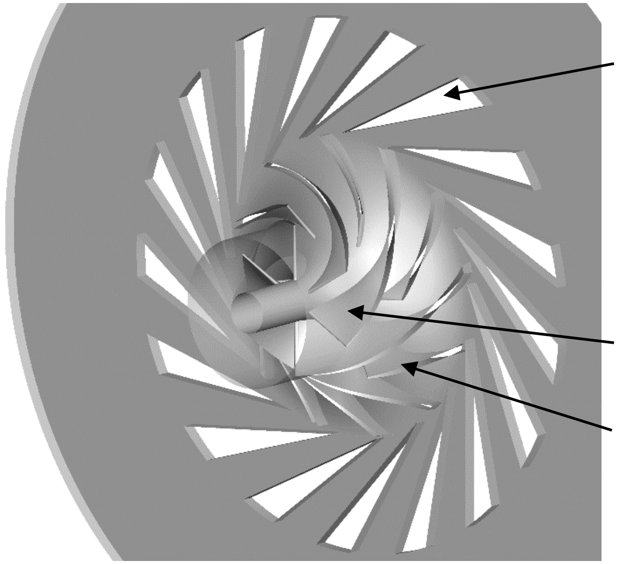

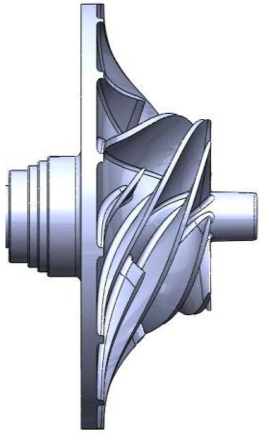

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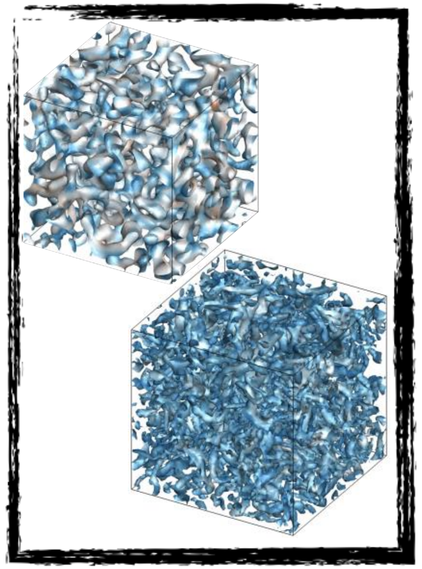
Methodology

CFD Solver

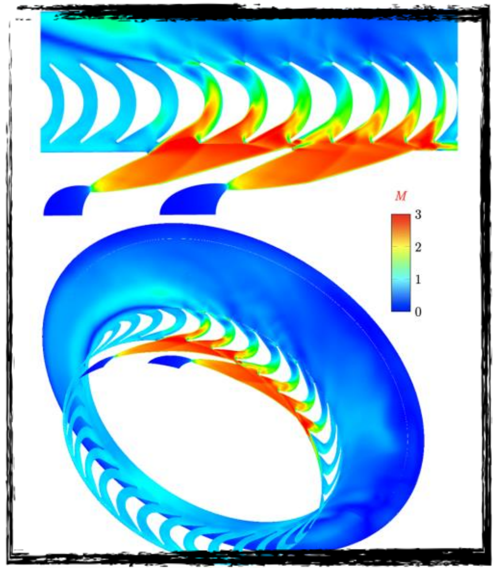
- In-house density based solver
- Hybrid parallelization
- Complex thermodynamic applications

CONDENSING WET STEAM (LES) [6]

DNS/LES



ORC [5]

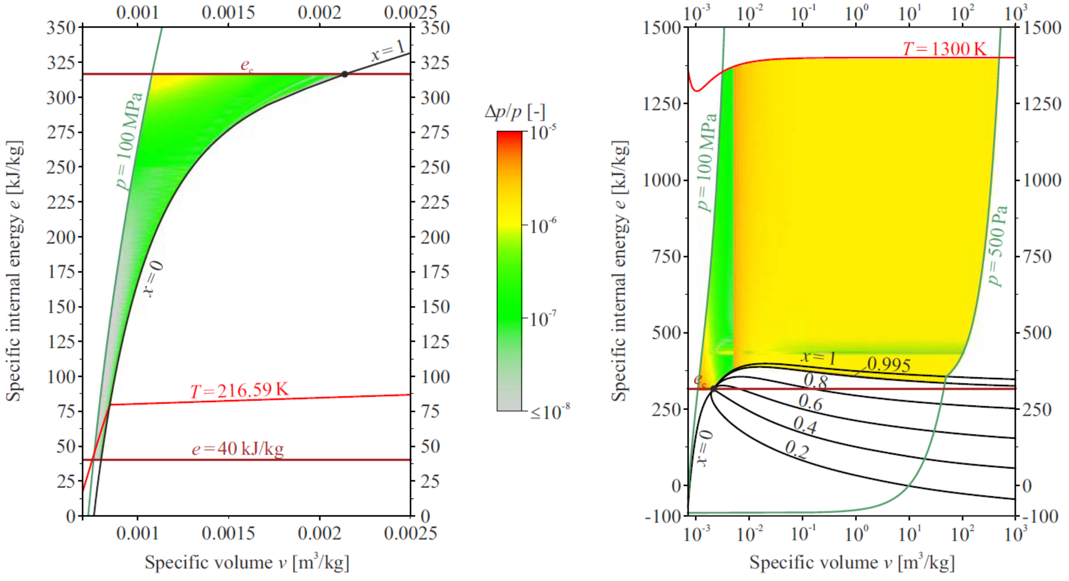


Methodology

Real Gas Property Tabulation

- Spline Based Table Lookup Method (SBTL) [2, 3]
  - Biquadratic polynomial spline interpolation
  - Continuous first derivatives
  - Numerically fast and consistent backward functions
  - Constructed on piecewise equidistant nodes
- Tabulated data is based on the Span-Wagner reference EOS [1] and correlations for viscosity and thermal conductivity [7, 8]
- Permissible deviations are within uncertainties of the underlying equations/correlations

Permissible deviations of spline-functions (CO_2 application)



[9]

SBTL function		liquid region	gas region
$p(v,e)$	$p \leq 2.5$ Mpa	$\lvert\Delta p/p\rvert < 0.001\%$	$\lvert\Delta p/p\rvert < 0.001\%$
	$p > 2.5$ Mpa	$\lvert\Delta p\rvert < 0.5$ kPa	
$T(v,e)$		$\lvert\Delta T\rvert < 1$ mK	$\lvert\Delta T\rvert < 1$ mK
$s(v,e)$		$\lvert\Delta s\rvert < 10^{-6}$ kJ/(kg K)	$\lvert\Delta s\rvert < 10^{-6}$ kJ/(kg K)
$w(v,e)$		$\lvert\Delta w/w\rvert < 0.001\%$	$\lvert\Delta w/w\rvert < 0.001\%$
$\eta(v,e)$		$\lvert\Delta\eta/\eta\rvert < 0.001\%$	$\lvert\Delta\eta/\eta\rvert < 0.001\%$
$\lambda(v,e)$		$\lvert\Delta\lambda/\lambda\rvert < 0.001\%$	$\lvert\Delta\lambda/\lambda\rvert < 0.001\%$

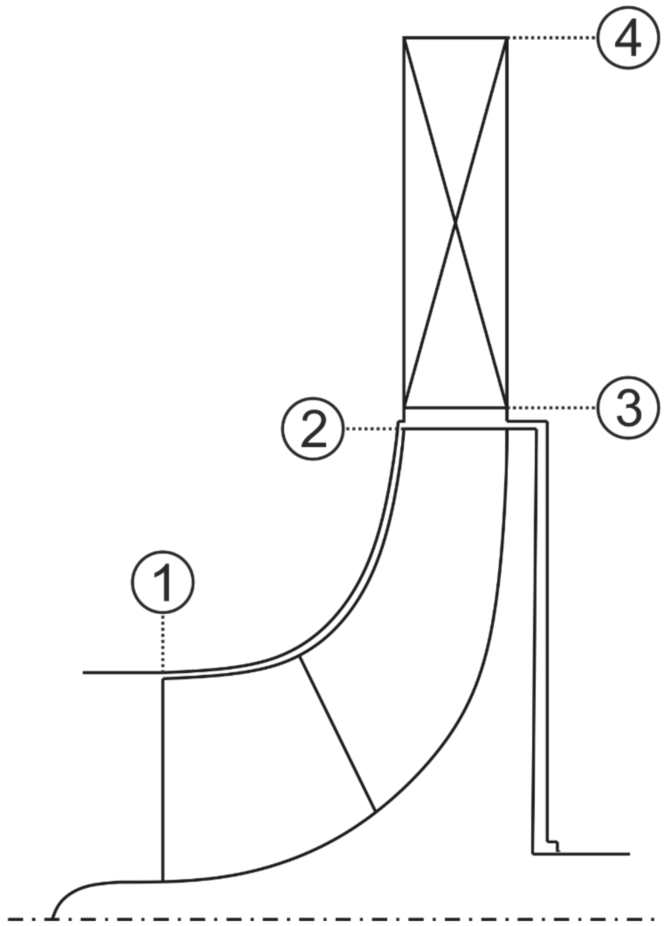
[2] M. Kunick. "Fast Calculation of Thermophysical Properties in Extensive Process Simulations with the Spline-Based Table Look-Up Method (SBTL)". Fortschrittberichte VDI, Nr. 618, Reihe 6, Energietechnik, 2018.

[3] M. Kunick et al. "CFD Analysis of Steam Turbines With the IAPWS Standard on the Spline-Based Table Look-Up Method (SBTL) for The Fast Calculation of Real Fluid Properties". Proceedings of ASME Turbo Expo 2015, ASME Paper No. GT2015-43984, 2015.

Methodology

Meanline Analysis Method

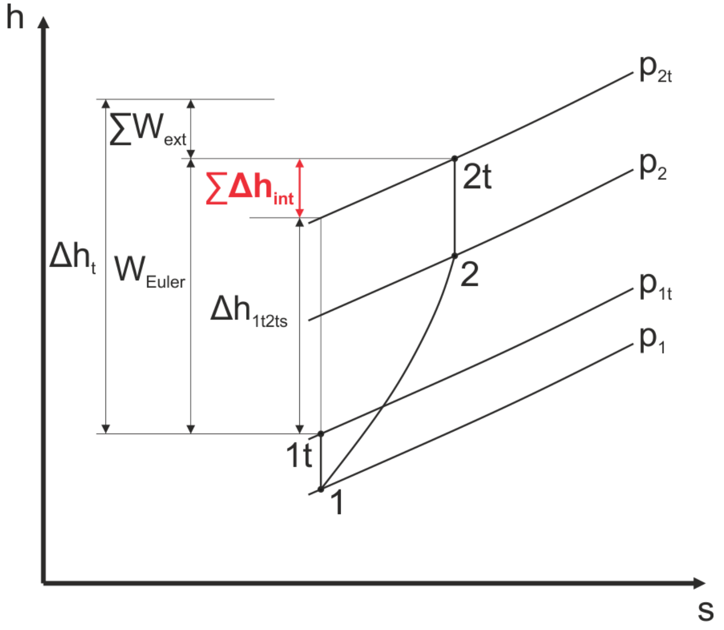
- Single-zone modeling approach
- Implemented in PYTHON with direct calls to the CoolProp [10] property library



Meanline Analysis Method

- Single-zone modeling approach
- Implemented in PYTHON with direct calls to the CoolProp [10] property library
- Applied loss model set is based on an optimised and validated set of internal and external loss for conventional centrifugal com-pressors (Oh et al. [11])

Loss mechanism	Loss model	Reference
Impeller		
Incidence	$\Delta h_{inc} = \sigma \cdot \frac{(w_{1\theta} - w_{1\theta,bl})^2}{2}$	Conrad et al. [12]
Blade loading	$\Delta h_{bl} = 0.05 \cdot D_f^2 \cdot u_2^2$	Coppage et al. [13]
Skin friction	$\Delta h_{sf} = 2c_f \frac{L_{fl}}{d_{hb}} \overline{w}^2$	Jansen [14]
Clearance	$\Delta h_{cl} = u_2^2 0.6 \frac{\delta_{cl}}{b_2} \frac{c_{2\theta}}{u_2} \times \sqrt{\frac{4\pi}{b_2 Z_{bl}} \left[\frac{r_{1t}^2 - r_{1h}^2}{(r_2 - r_{1t})(1 - \rho_2/\rho_1)}\right] \frac{c_{2\theta}}{u_2} \frac{c_{1m}}{u_2}}$	Jansen [14]
Mixing	$\Delta h_{mix} = \frac{c_2^2}{2[1 + (c_{2\theta}/c_{2m})^2]} \cdot \left[\frac{1 - \varepsilon - B}{1 - \varepsilon}\right]^2$	Johnston & Dean [15]



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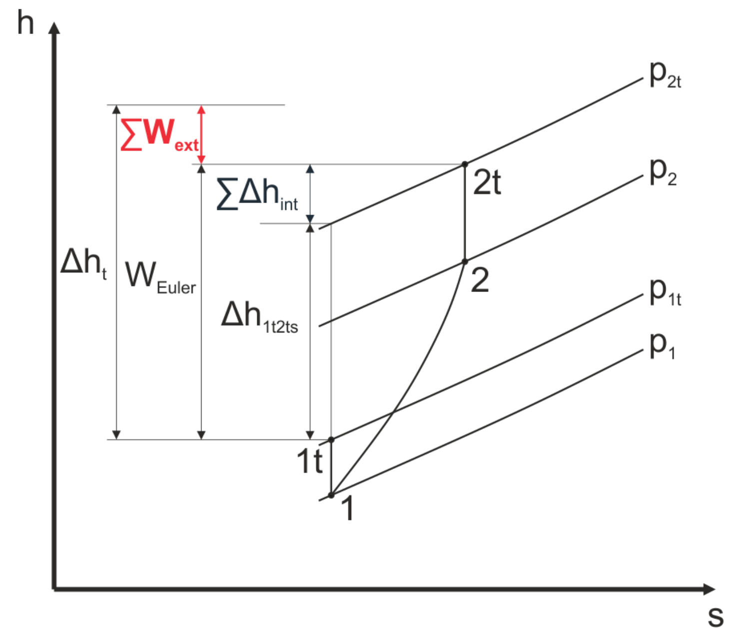
Loss mechanism	Loss model	Reference
External		
Disk Friction	$W_{df} = f_{df}\frac{\bar{\rho} r_2^2 u_2^3}{4\dot{m}}$	Daily and Nece [16] as quoted by Oh et al. [11]
Recirculation	$W_{rc} = 8 \cdot 10^{-5} \sinh(3.5\alpha_2^3)\, D_f^2 u_2^2$	Oh et al. [11]
Leakage	$W_{lk} = \frac{\dot{m}_{cl} u_{cl} u_2}{2\dot{m}}$	Aungier [17]



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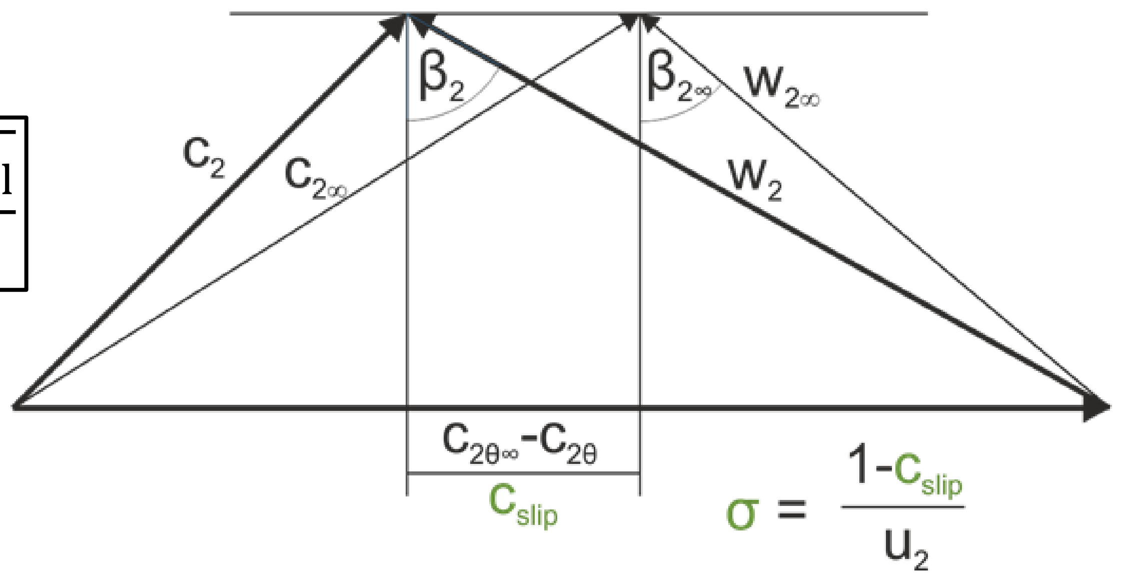
$$\sigma = 1 - \frac{\sqrt{\cos \beta_{2,bl}}}{Z_{bl}^2}$$



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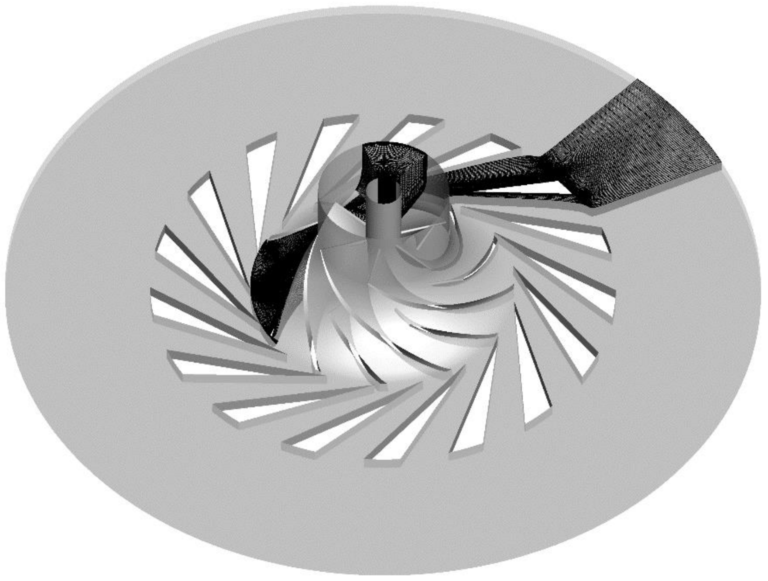
- Diffuser model adopted from Aungier [19]

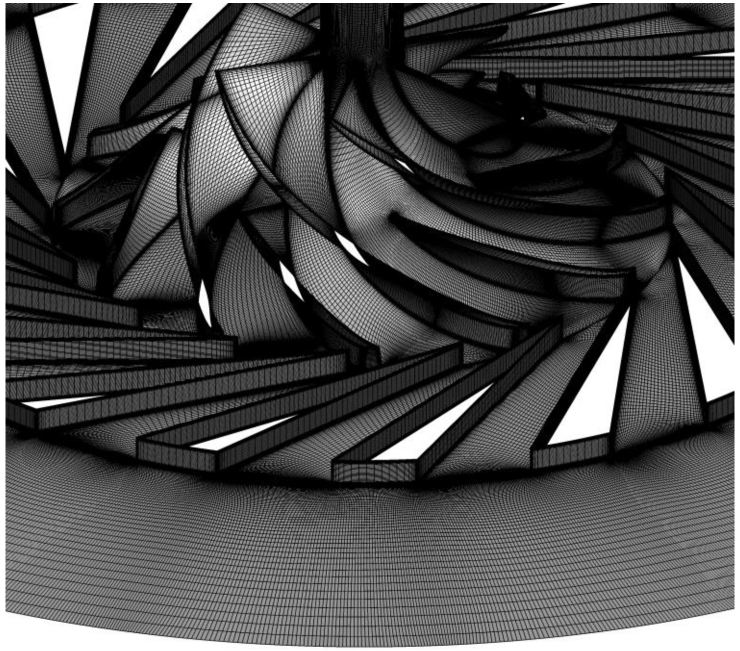
Loss mechanism	Loss model	Reference
Diffuser		
Incidence	$\bar{\omega}_{inc} = \begin{cases} 0.8[(c_3 - c_3^*)/c_3]^2 & c_3 \leq c_{3S} \\ 0.8[((c_3/c_{3S})^2 - 1)\, c_{th}^2/c_3^2 + (c_{3S} - c_3^*)^2/c_{3S}^2] & c_3 > c_{3S} \end{cases}$	Aungier [19]
Skin friction	$\bar{\omega}_{sf} = 4c_{f,diff}(\bar{c}/c_3)^2\, L_B/d_{h,diff}/(2\delta/d_{h,diff})^{0.25}$	Aungier [19]
Mixing	$\bar{\omega}_{mix} = [(c_{m,wake} - c_{m,mix})/c_3]^2$	Aungier [19]

Methodology

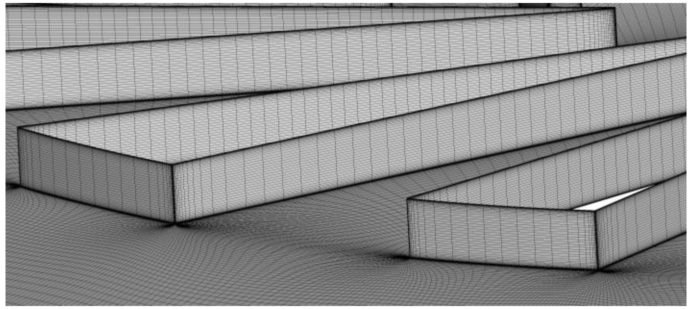
CFD Analysis - Numerical Setup

- Steady state RANS simulations
  - Second order AUSM+ scheme [20]
  - Implicit LUSGS scheme
- Spalart-Allmaras turbulence model [21]
- Homogenous equilibrium mixture (HEM)
- Block structured mesh
  - No wall functions: y+ < 5
  - ≈ 1.5 mio. cells
    for single main + splitter blade
  - ≈ 630k cells for single diffuser passage
- Mixing-Plane RS-Interface

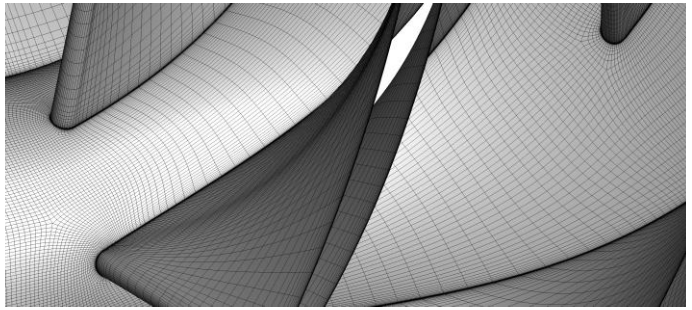




Replicated surface mesh



Diffuser trailing edge



Impeller blade passage

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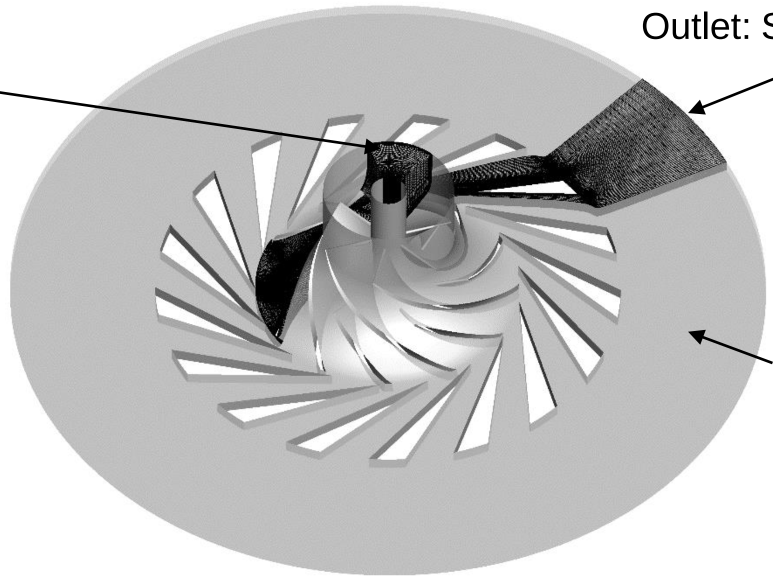

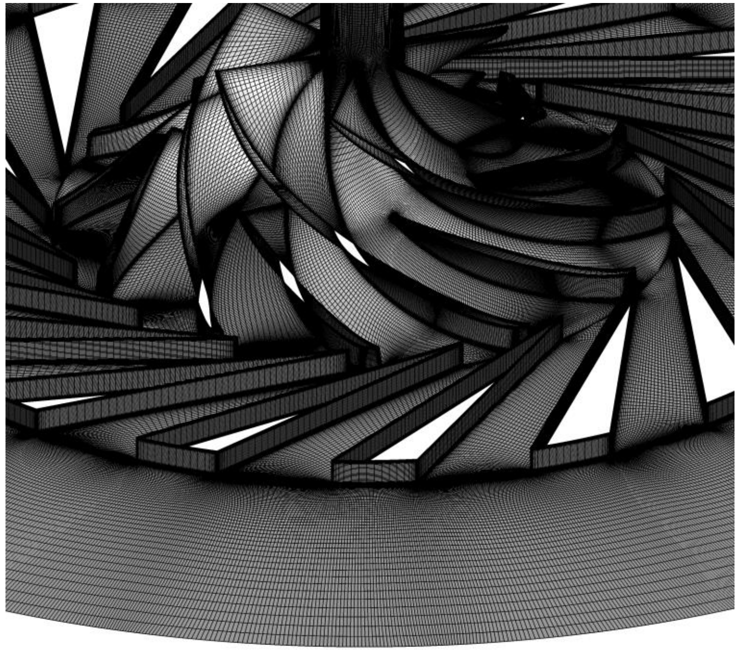

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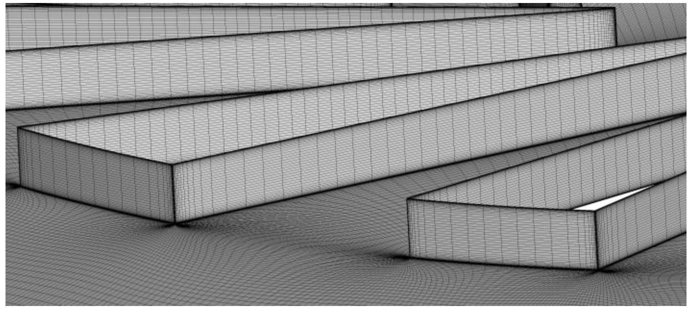

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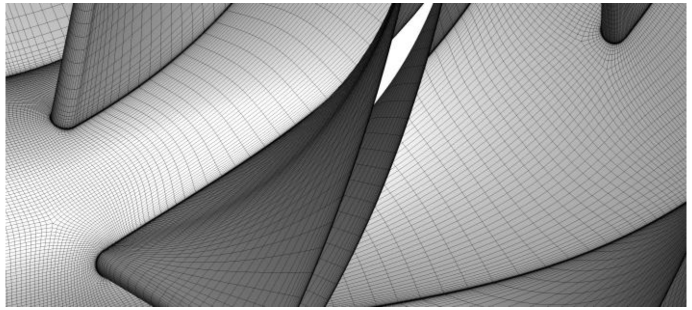
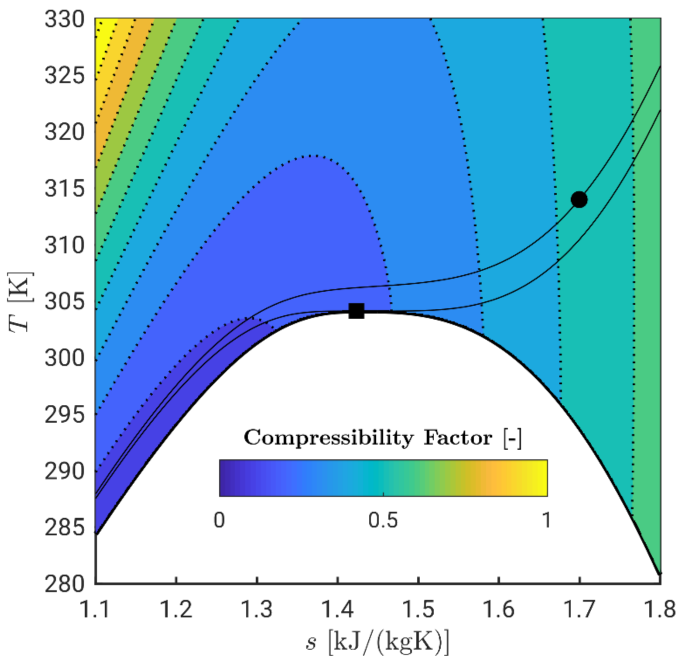


Impeller blade passage

Compressor Performance

Investigated Compressor Operating Condition

- Inlet state:
  77.5 bar ($p/p_c \approx 1.04$), 314 K ($T/T_c \approx 1.03$), $Z \approx 0.53$
- 50 krpm speedline calculation (off-design)
  → most data available
- Comparison with experimental data of Wright et al. [4, 22] and Fuller & Eisemann [23] and previous numerical study (Karaefe et al. [9]) considering the impeller geometry



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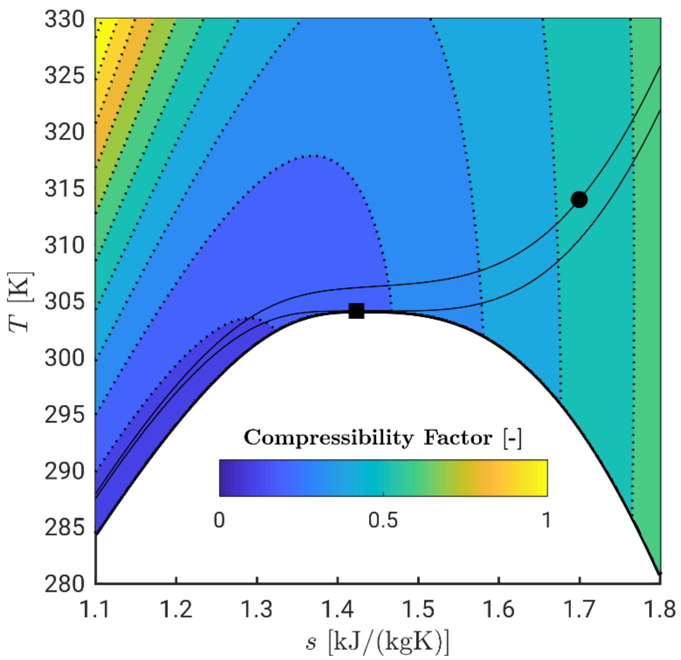
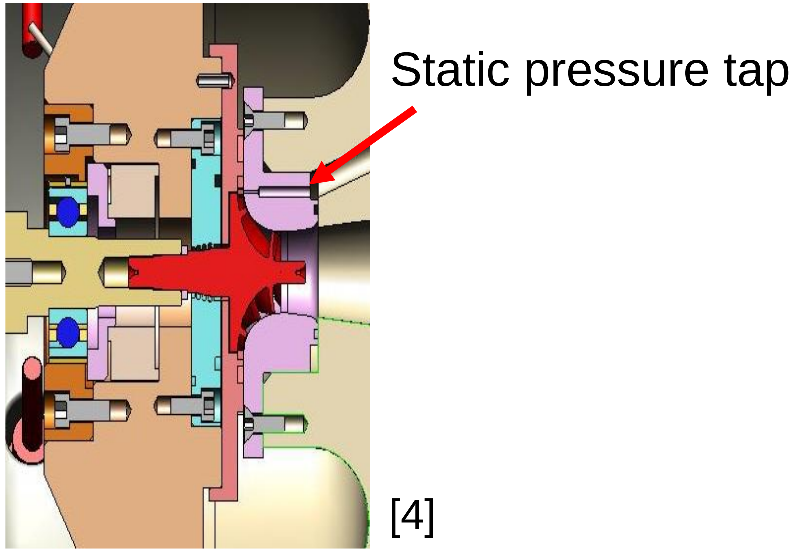
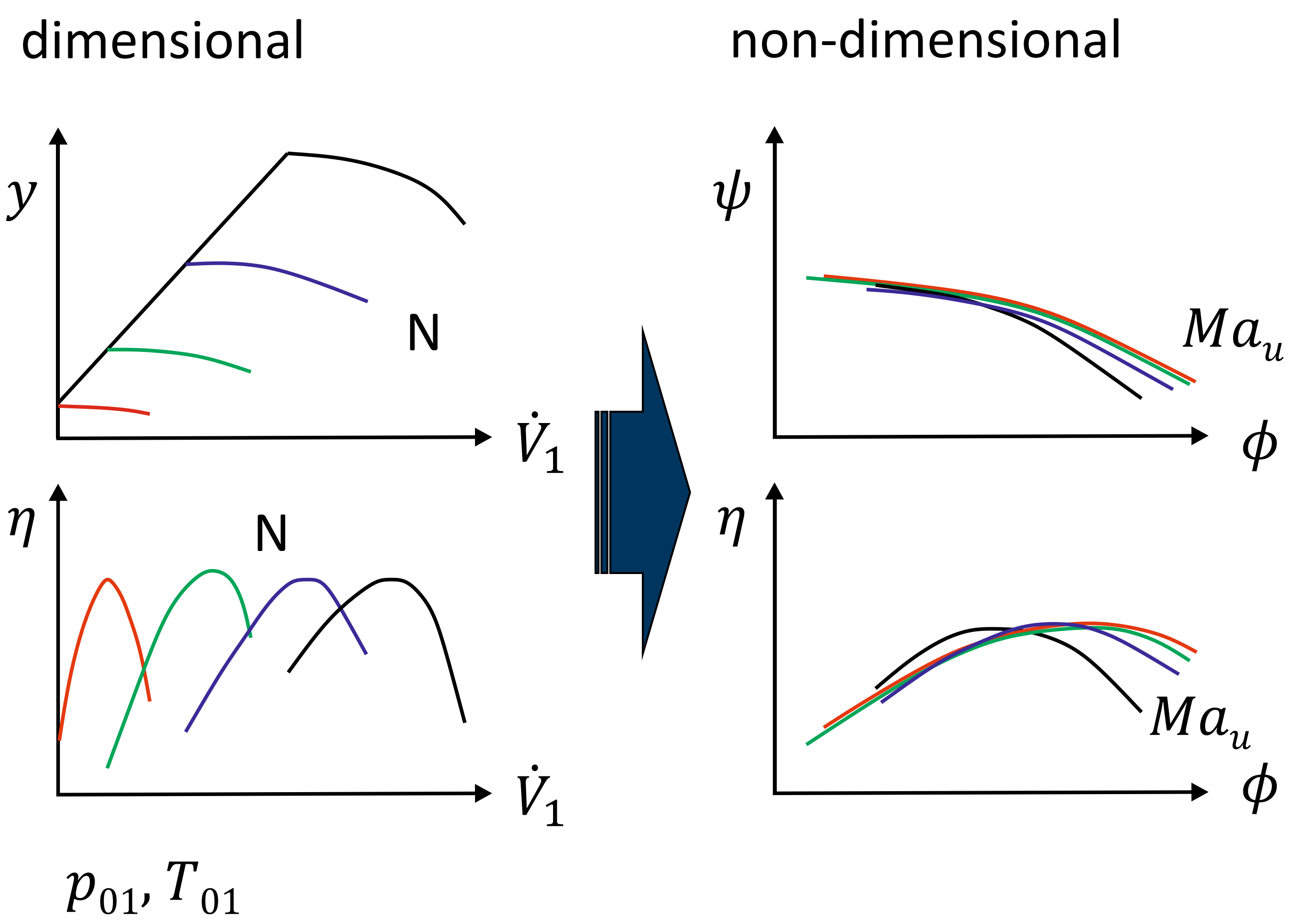
- Experimental performance assessments (total-to-static) are interpreted to be associated with the impeller wheel (static pressure tap at impeller exit)
- Strong variation of experimental inlet states
  → corrected and non-dimensional performance map representation





[4]

Performance Assessment

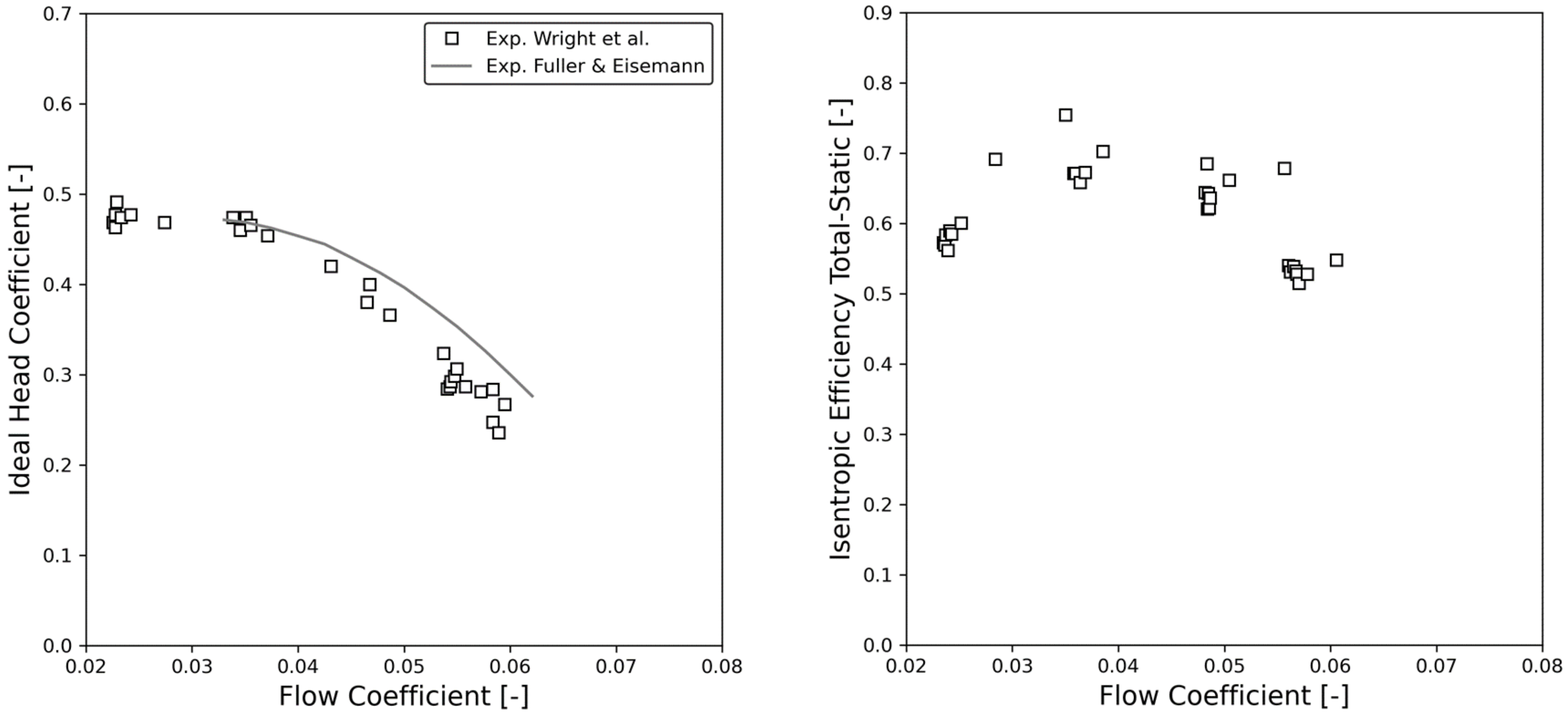


$$\phi = \frac{4\dot{V}_1}{\pi d_2^2 u_2}$$ Flow Coefficient

$$\psi_{12} = \frac{h_{2s} - h_{01}}{u_2^2}$$ Ideal Head Coefficient

$$\eta_{s,12} = \frac{h_{2s} - h_{01}}{h_{02} - h_{01}}$$ Isentropic Efficiency

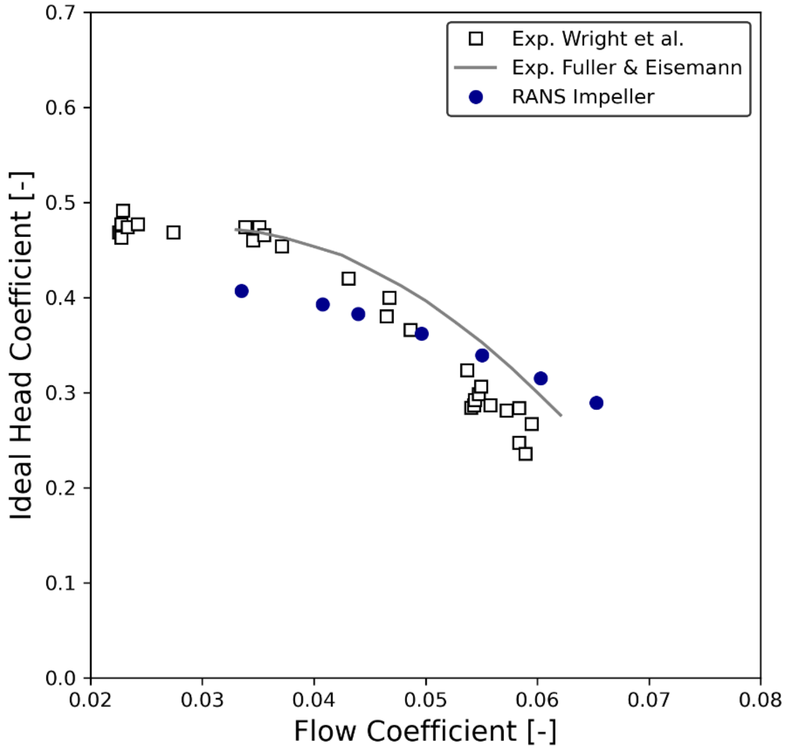
Non-Dimensional Performance

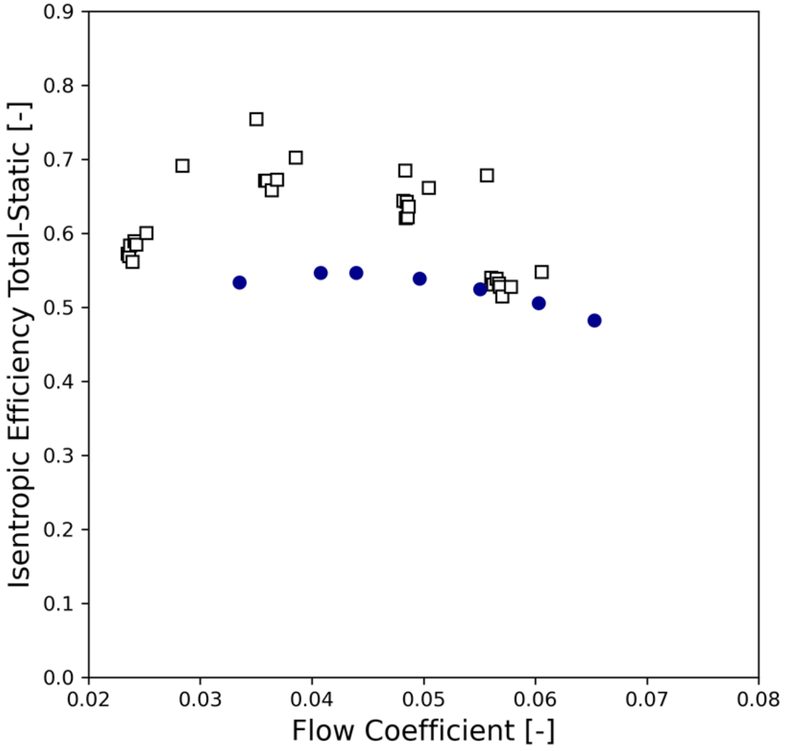


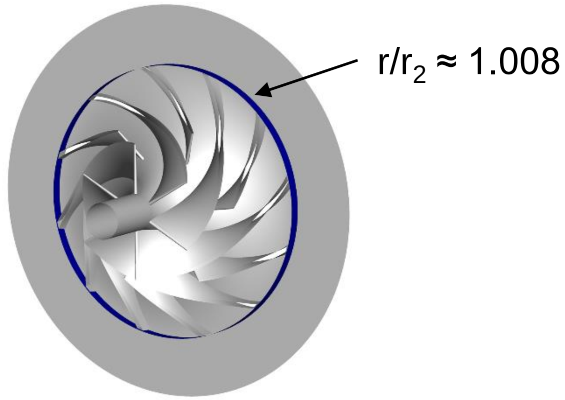
Compressor Performance

Non-Dimensional Performance

- RANS - Impeller only [9]
  - Flatter head characteristic
  - Reduced efficiencies
  - Surge comparable
  - Flow coefficient for max. efficiency comparable



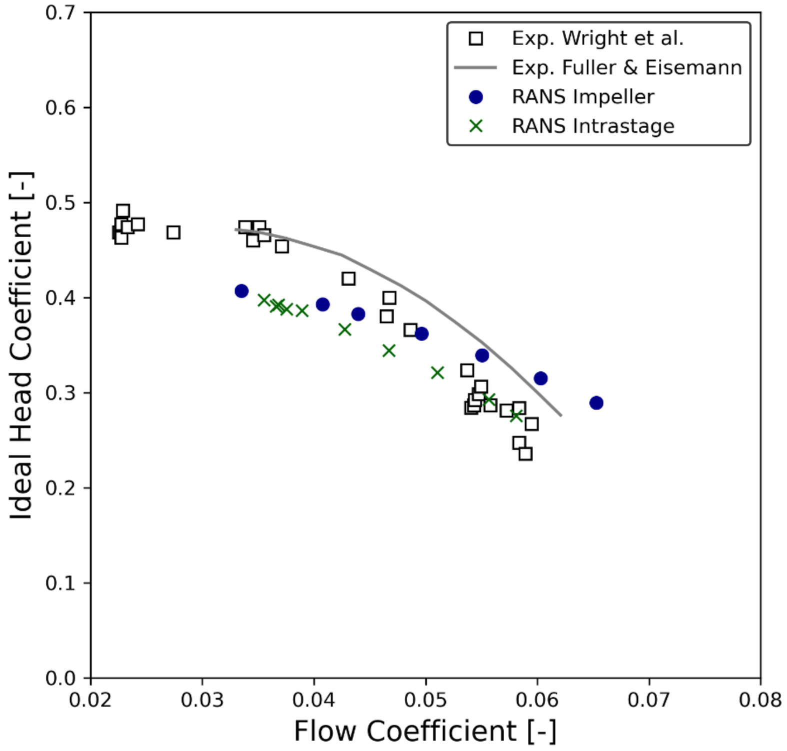


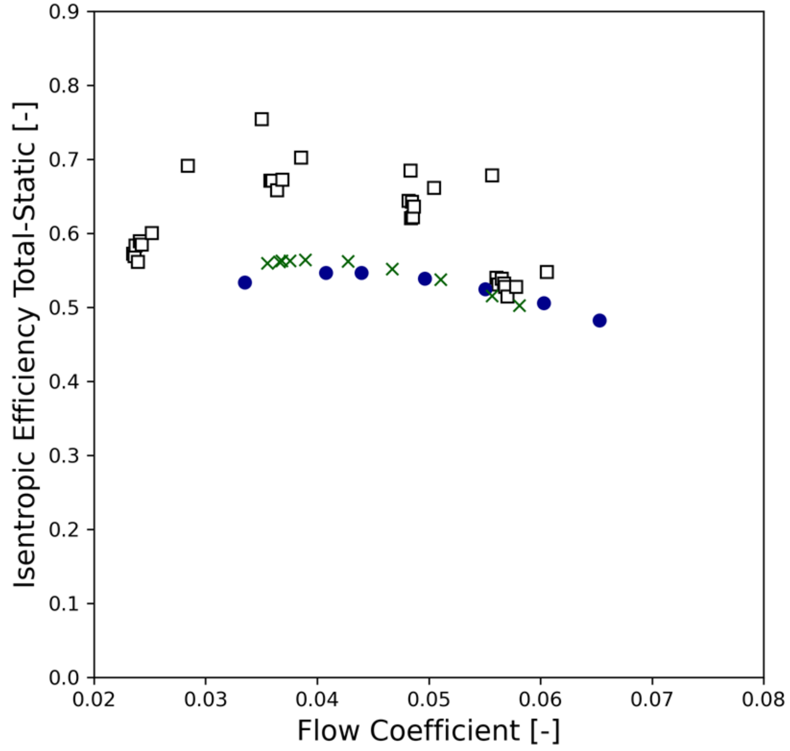


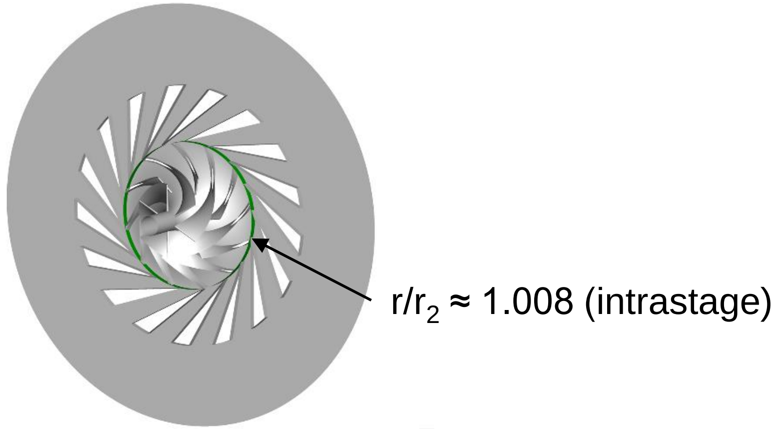
Compressor Performance

Non-Dimensional Performance

- RANS - Impeller performance assessment at intrastage position
  - Steeper head characteristic compared to previous setup
  - Comparable efficiencies between both setups





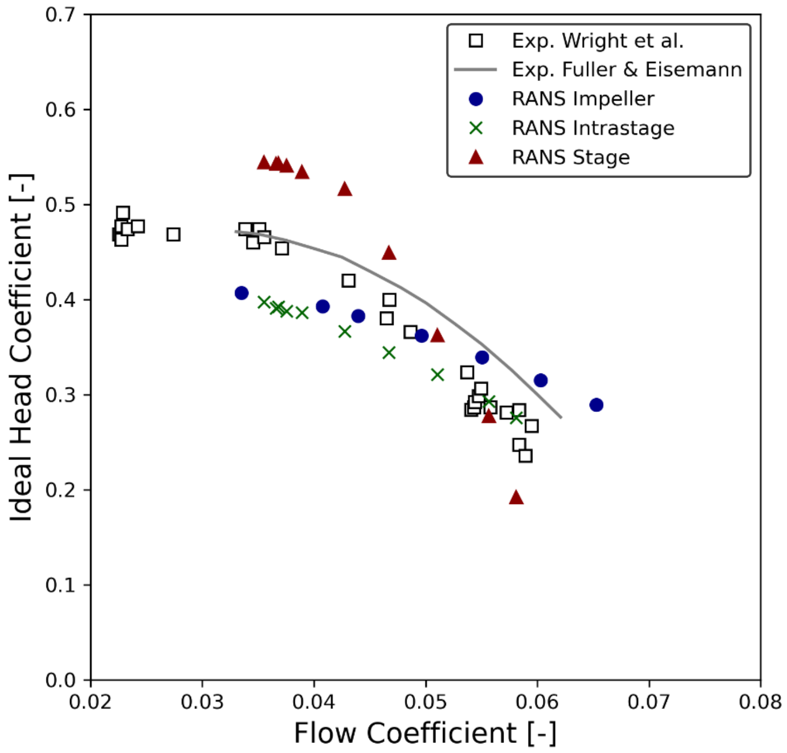


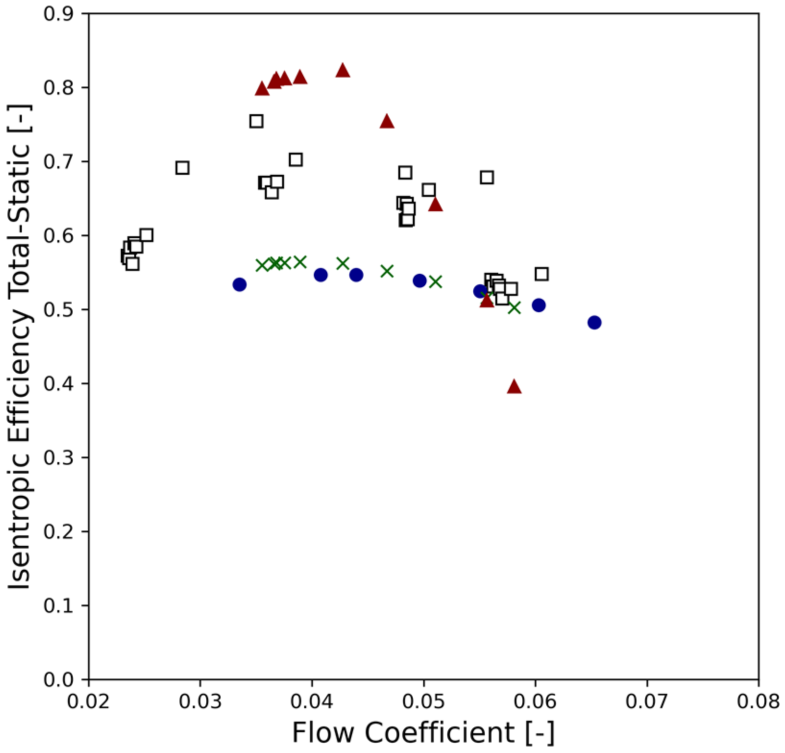
Compressor Performance

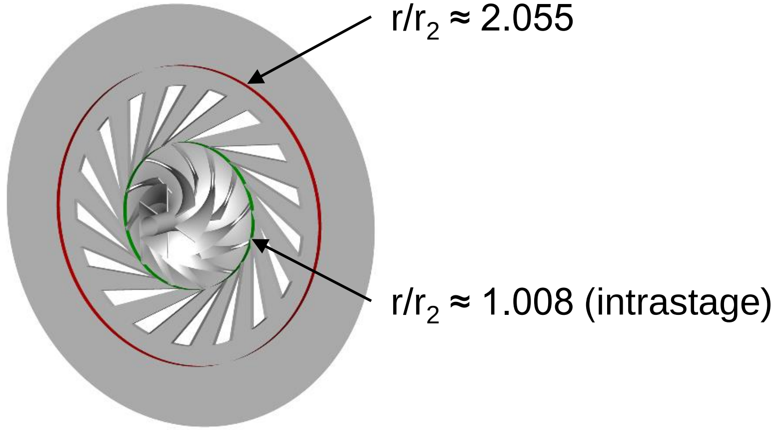
Non-Dimensional Performance

- RANS - Impeller performance assessment at intrastage position
  - Steeper head characteristic compared to previous setup
  - Comparable efficiencies between both setups

- RANS - Stage performance assessment
  - Ideal head rise of 13-41% for $\phi \approx 0.036 \ldots 0.051$
  - Maximum efficiency ≈ 82% (t-s)
  - Steep decline in head and efficiency for $\phi > 0.043$

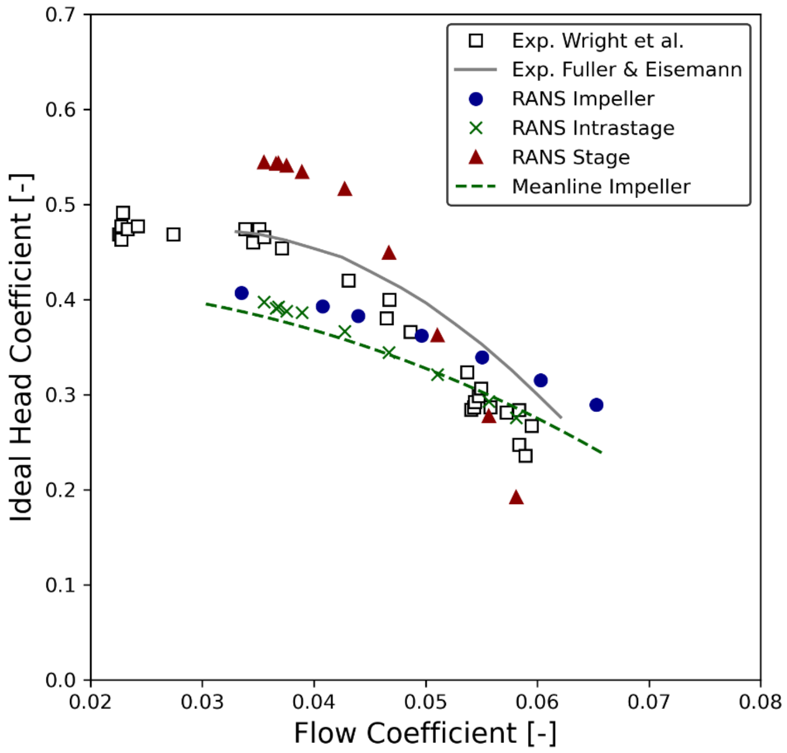


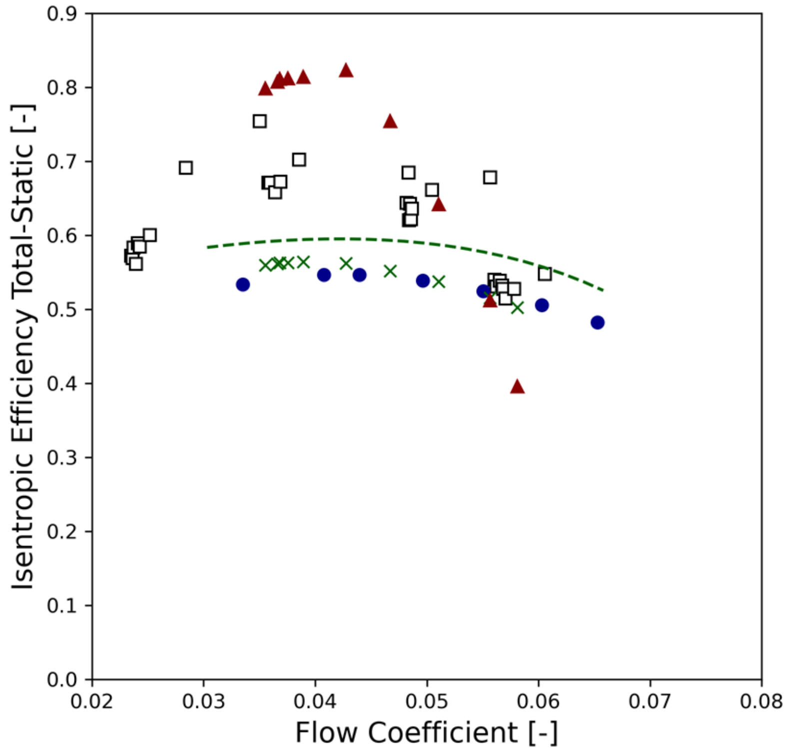


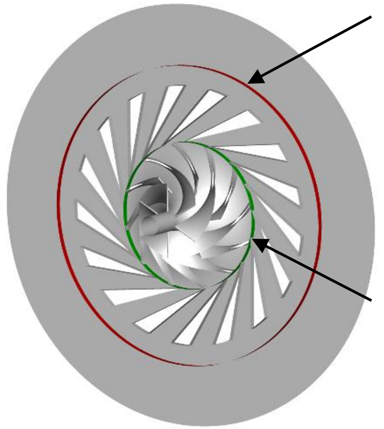


Non-Dimensional Performance

- Meanline impeller assessment
  - Ideal head curve shows better agreement with the intrastage impeller assessment
  - Maximum impeller efficiency ≈ 60% (t-s)



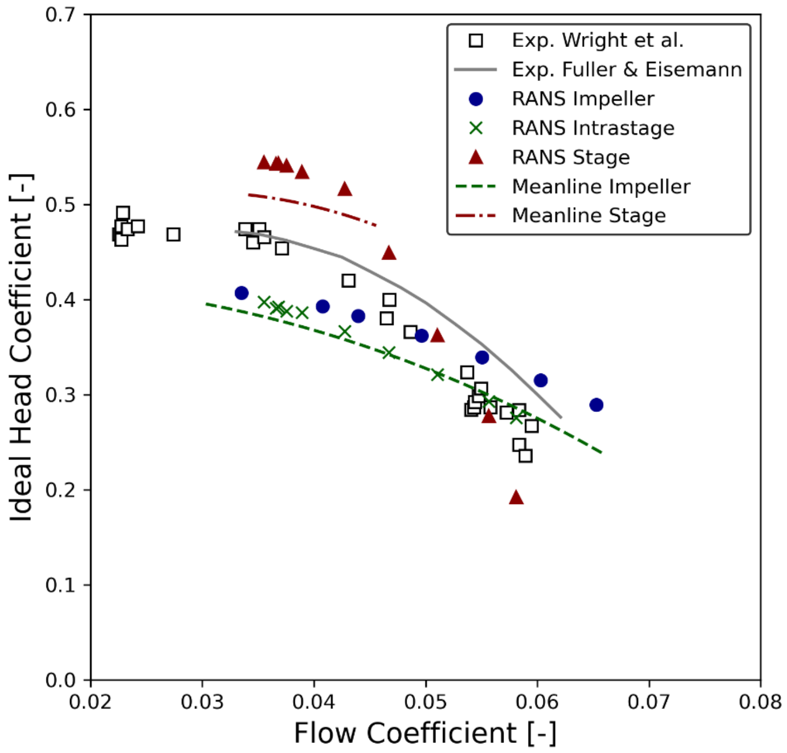


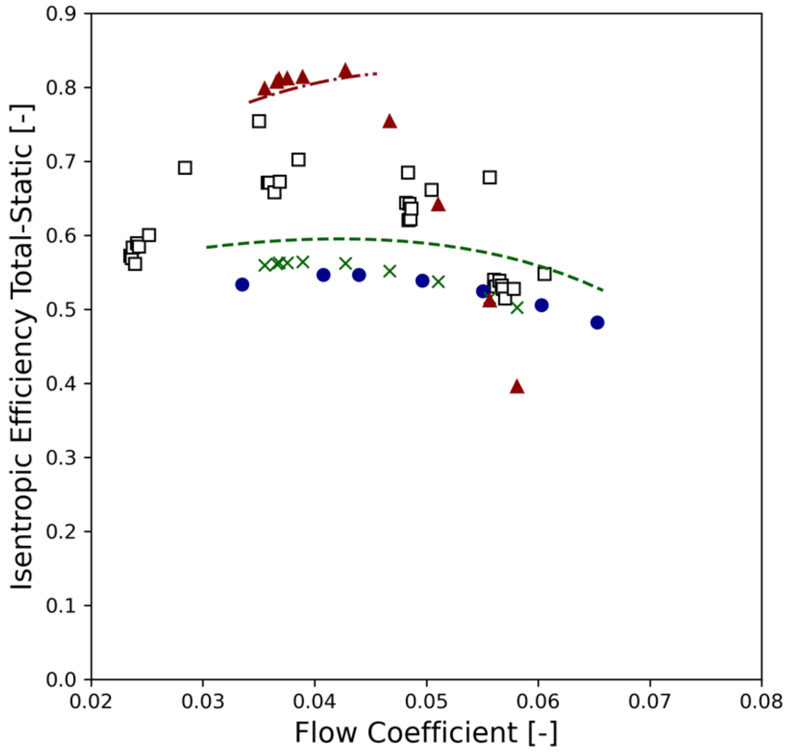


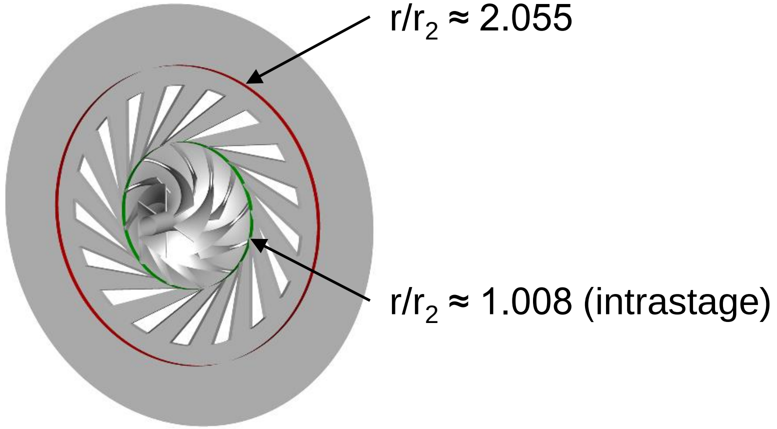
Compressor Performance

Non-Dimensional Performance

- Meanline impeller assessment
  - Ideal head curve shows better agreement with the intrastage impeller assessment
  - Maximum impeller efficiency ≈ 60% (t-s)
- Meanline stage assessment
  - 6-7% reduced ideal head compared to RANS calculations for flow coefficients up to $\phi \approx 0.043$
  - Abrupt decline in ideal head and efficiency can not be resembled by the diffuser model

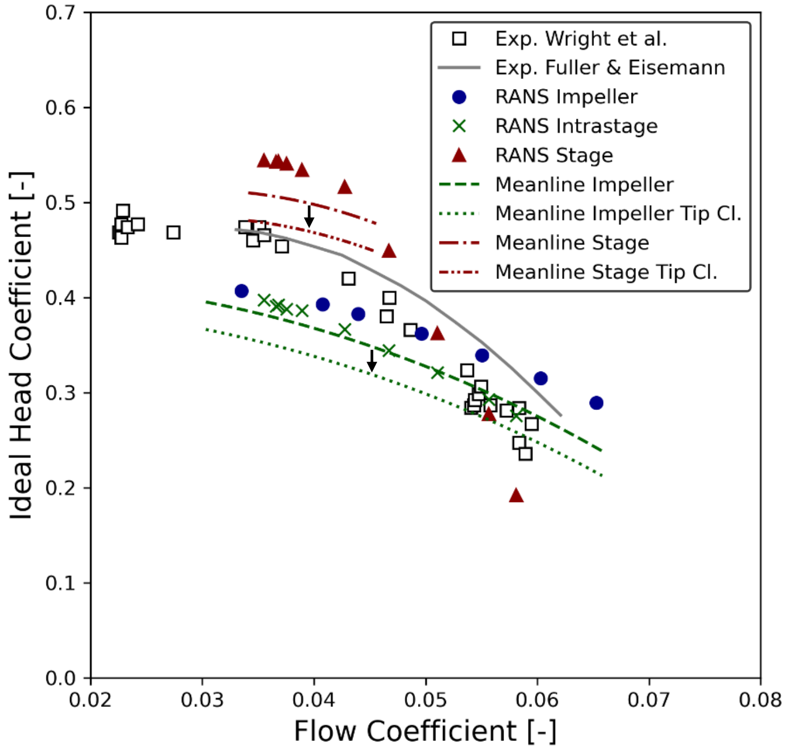


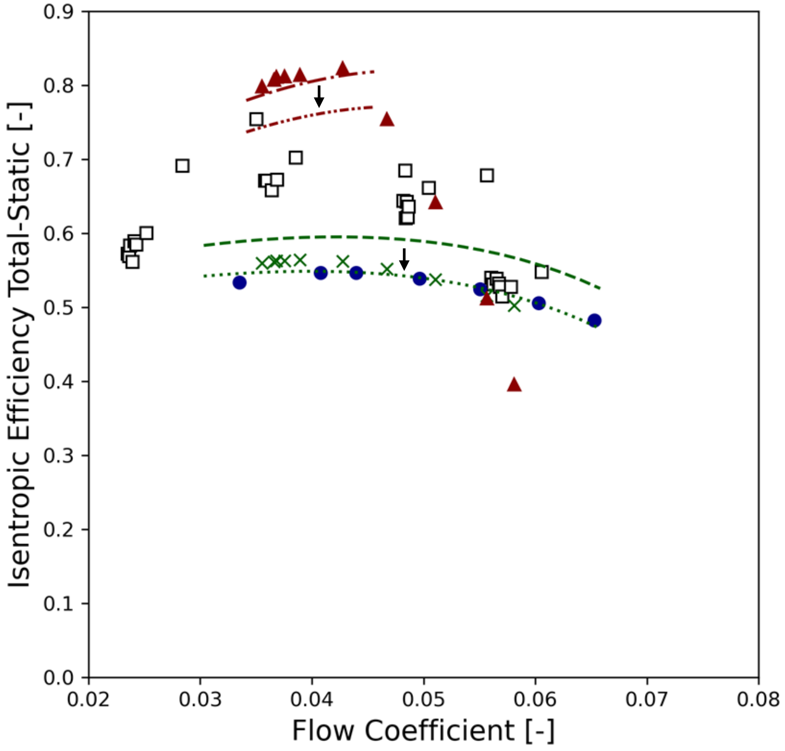


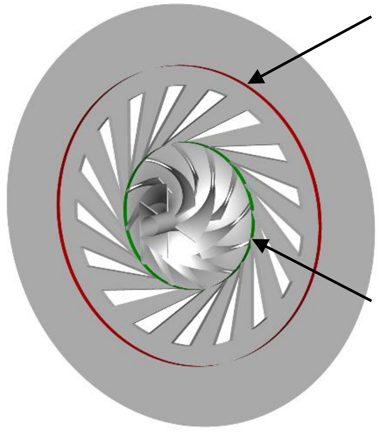


Non-Dimensional Performance

- Consideration of impeller tip clearance in meanline assessment:
  - 7-11% decrease in impeller head generation
  - 4-5 percentage points decrease in impeller efficiency







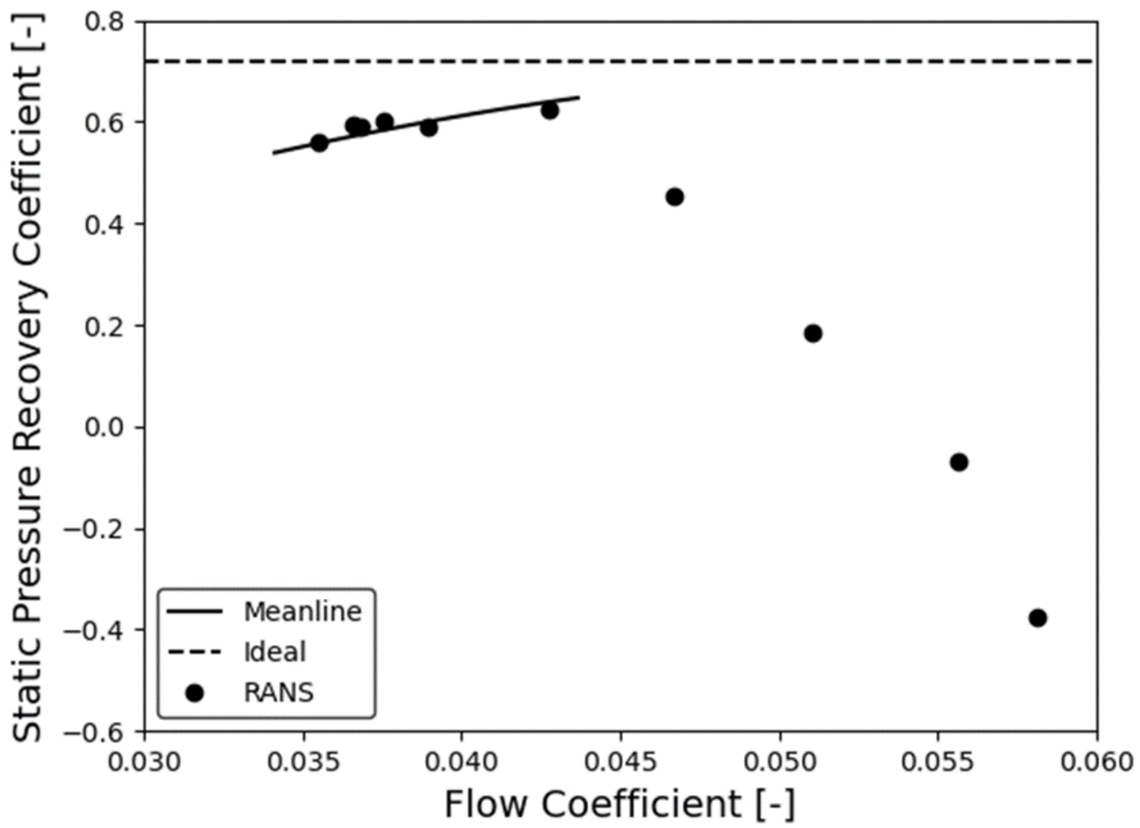
Compressor Performance

TTF RUB

Diffuser performance

- Efficient pressure recovery in the range $\phi \approx 0.036 \ldots 0.043$
- Good agreement between meanline and RANS prediction for the flow range with efficient recovery

$$c_p = \frac{p_{out} - p_{in}}{p_{0,in} - p_{in}}$$ Static Pressure Recovery Coefficient



Compressor Performance

Diffuser performance

- Efficient pressure recovery in the range $\phi \approx 0.036 \ldots 0.043$
- Good agreement between meanline and RANS prediction for the flow range with efficient recovery
- RANS:
  - Continuous decline in c_p for $\phi > 0.043$
  - Negative c_p for $\phi > 0.051$ $(p_{0,out} < p_{in})$

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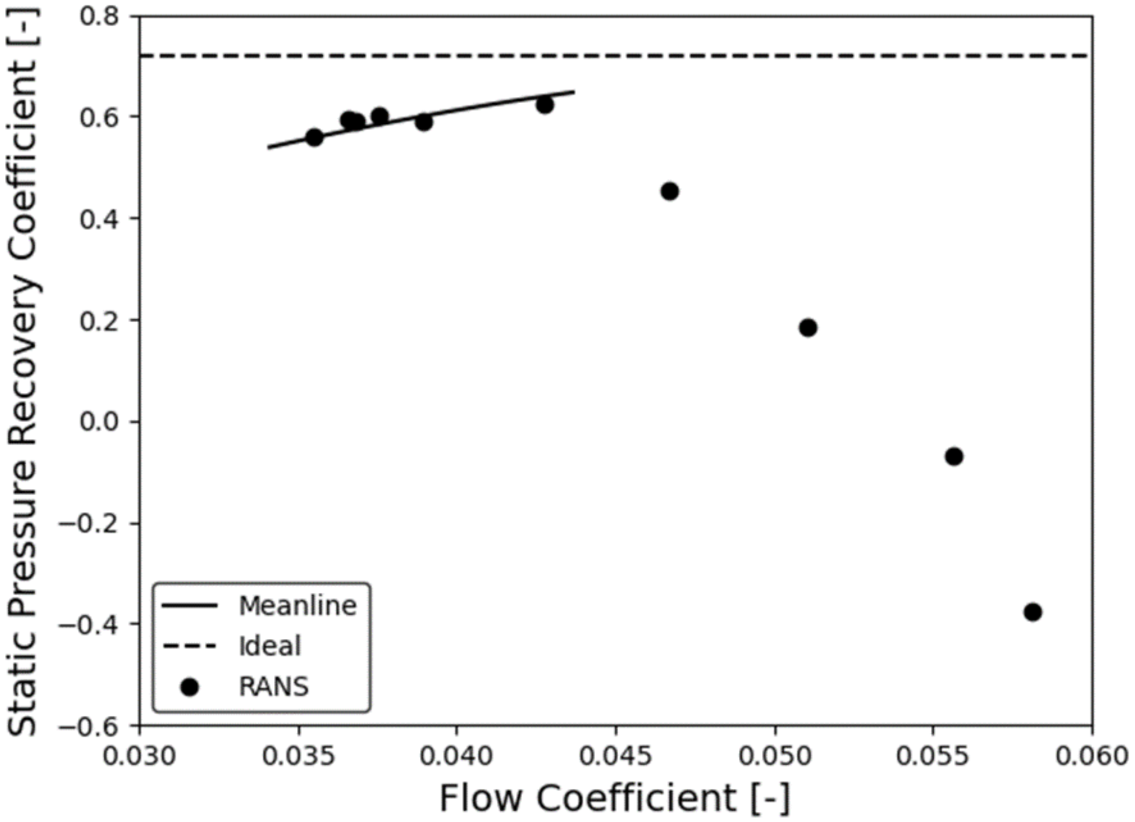

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Diffuser performance

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- RANS:
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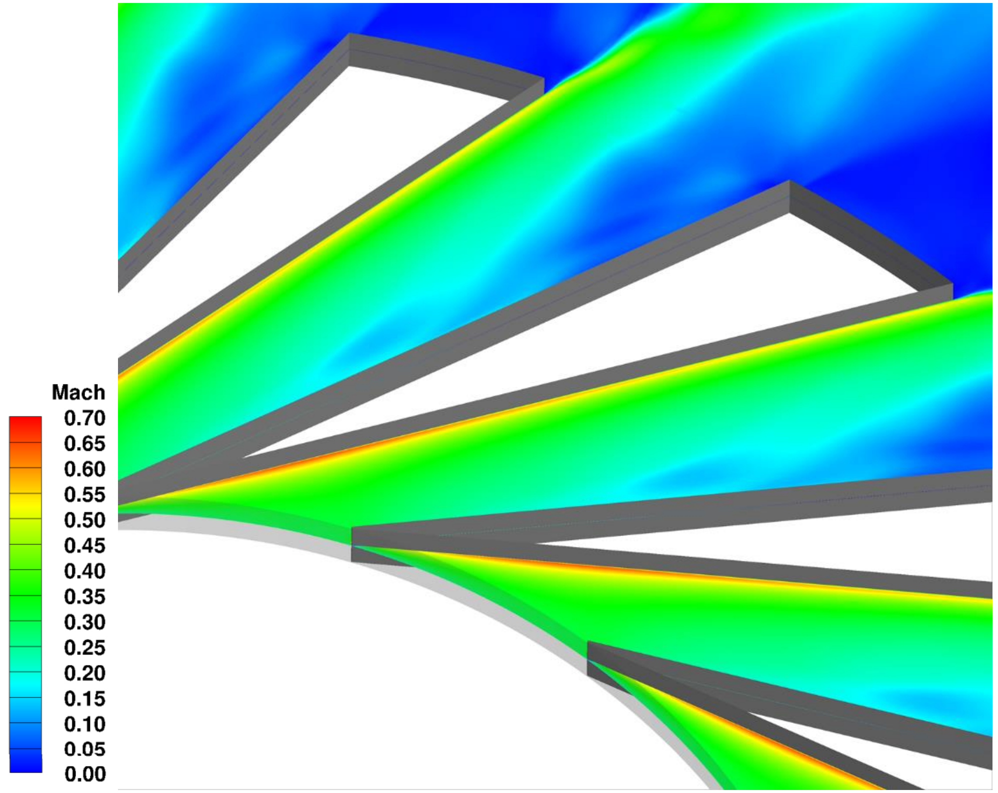
  - Negative c_p for $\phi > 0.051$ $(p_{0,out} < p_{in})$
  - Flow separation in channel diffuser passage

$$c_p = \frac{p_{out} - p_{in}}{p_{0,in} - p_{in}}$$ Static Pressure Recovery Coefficient



Contours of Mach number at 50 % span for $\phi \approx 0.058$

Compressor Performance

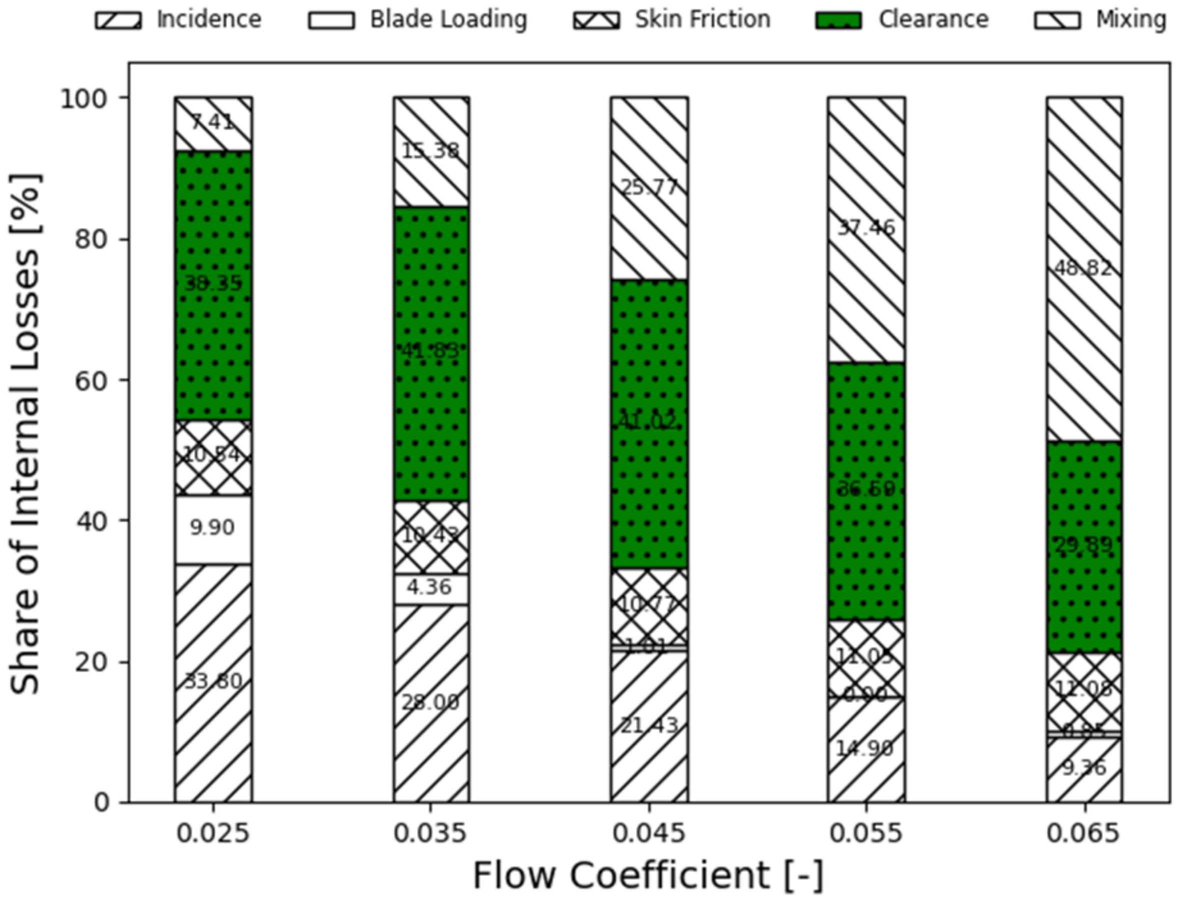
TTF RUB

Meanline Loss Distribution

- Clearance loss with significant share over the entire flow range (≈ 30-42%)

  SNL: $\frac{\delta}{d_2} \approx 0.007$

  Eckardt Impeller: $\frac{\delta}{d_2} \approx 0.001$



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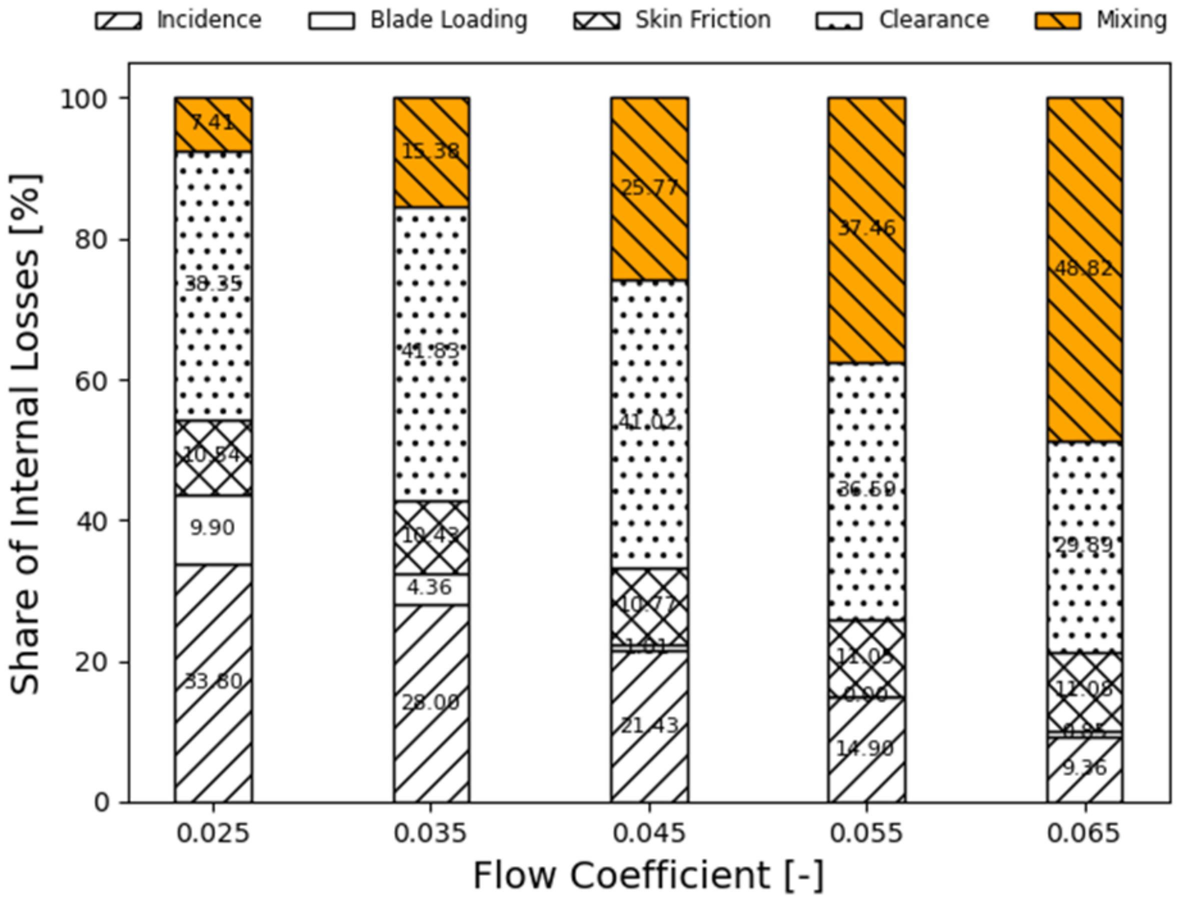
- Wake mixing losses dominant in meanline prediction at high flow coefficients

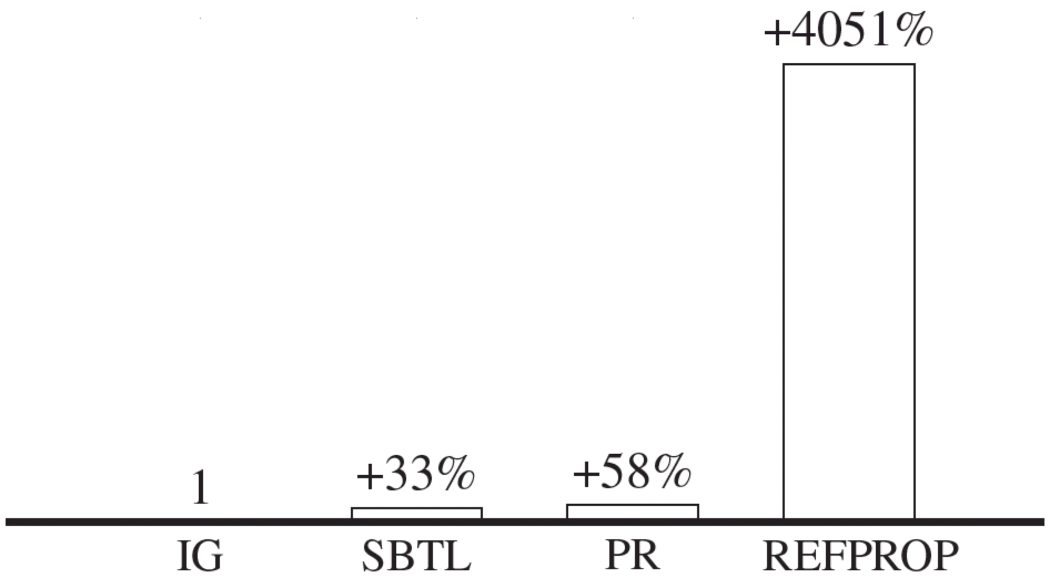


Evaluation of Computational Speed

TTF RUB

Benchmark

- IG and PR simulations performed without tabulation
- Direct calls to REFPROP library
- Further reduction of overhead might be expected in future versions of the SBTL library (2% overhead demonstrated for the highly optimised steam version)



Conclusion and Consecutive Work

TTF RUB

Conclusion

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- Reasonable performance metrics derived despite approximations of the candidate compressor geometry

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Consecutive Work

- Integration of metastable states and assessment of non-equilibrium condensation

Conclusion and Consecutive Work

TTF RUB

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Conclusion and Consecutive Work

Conclusion

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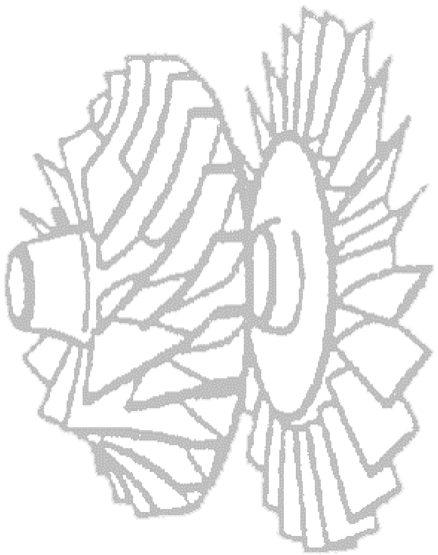
Consecutive Work

- Integration of metastable states and assessment of non-equilibrium condensation
- Analysis of the aerodynamic loss distribution through CFD
- Transient simulations for improved assessment of rotor-stator interaction

THANK YOU

Renan Emre Karaefe

emre.karaefe@rub.de



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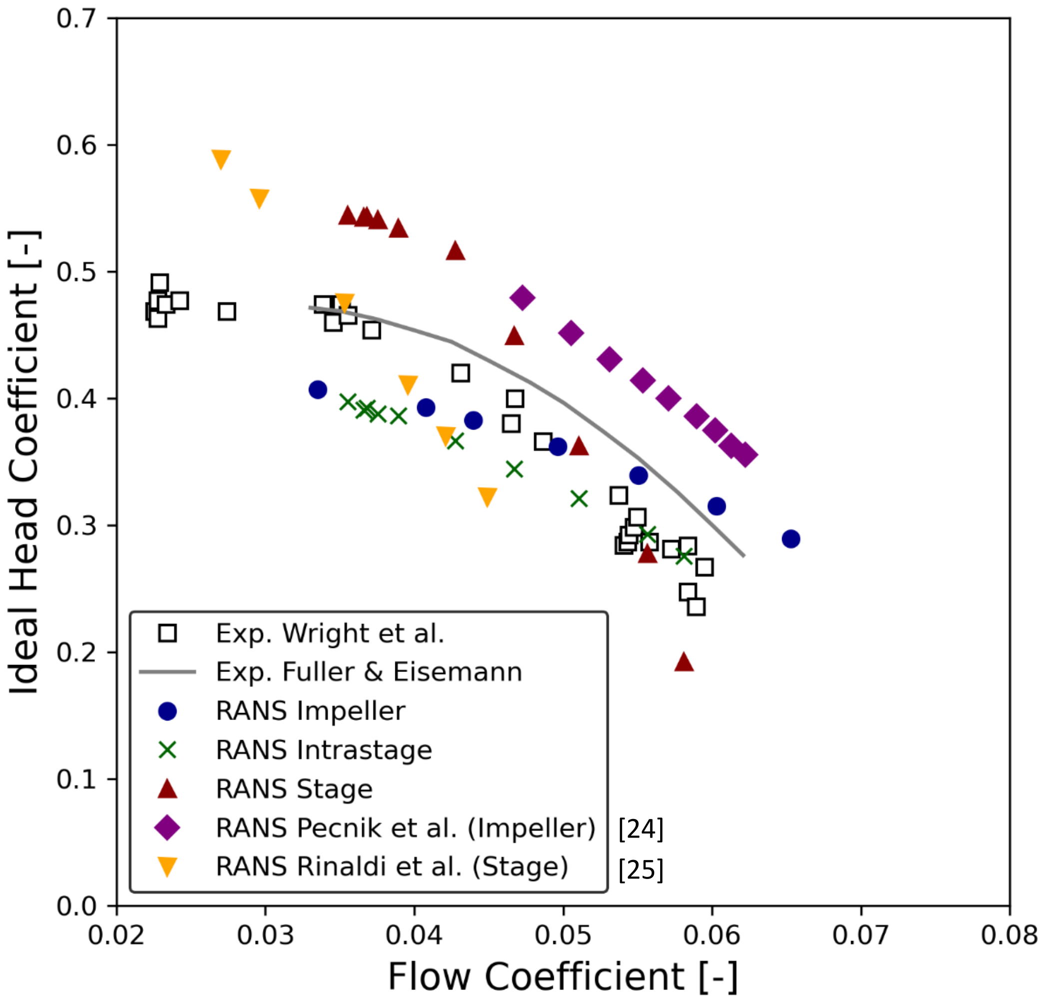
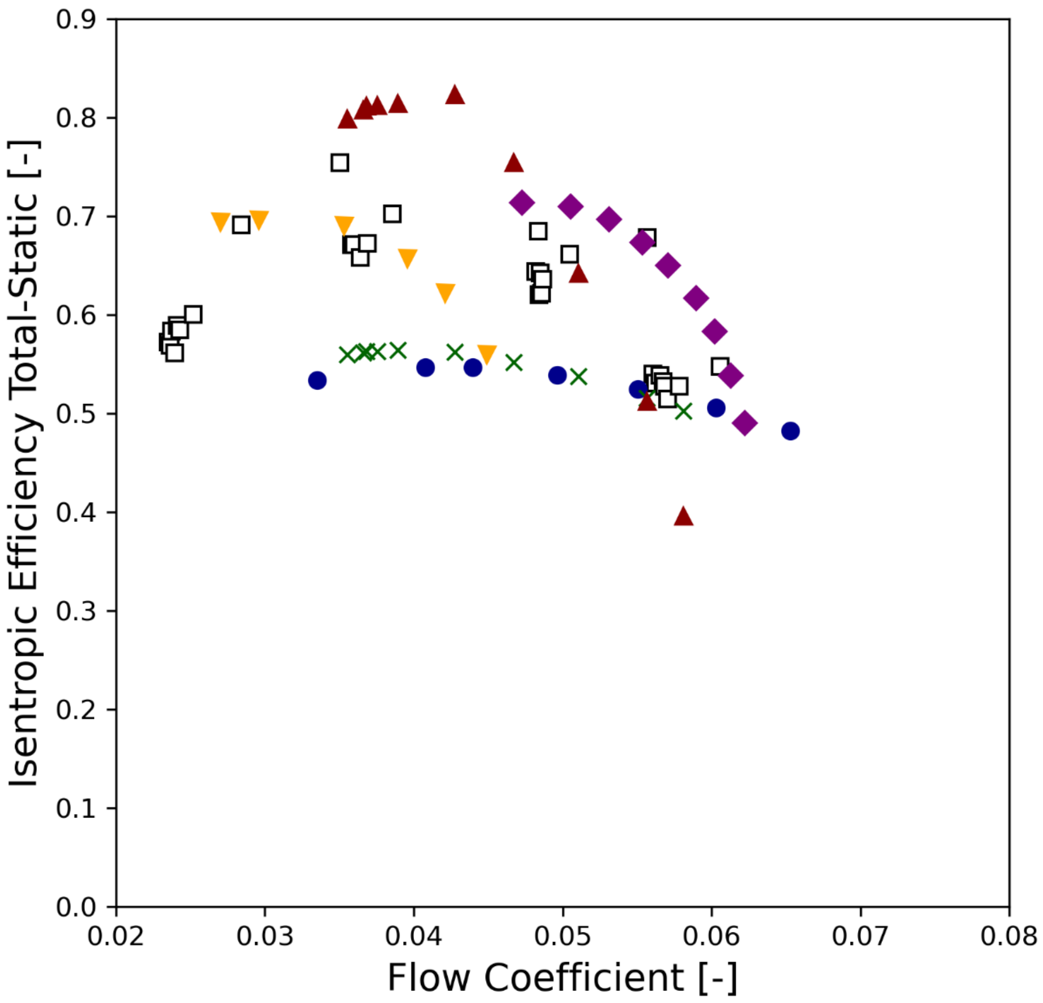
Additional Content





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