RUB

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NUMERICAL INVESTIGATION OF A SUPERCRITICAL CO2 CENTRIFUGAL COMPRESSOR WITH AN IN-HOUSE DENSITY BASED COMPRESSIBLE CFD SOLVER

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Motivation

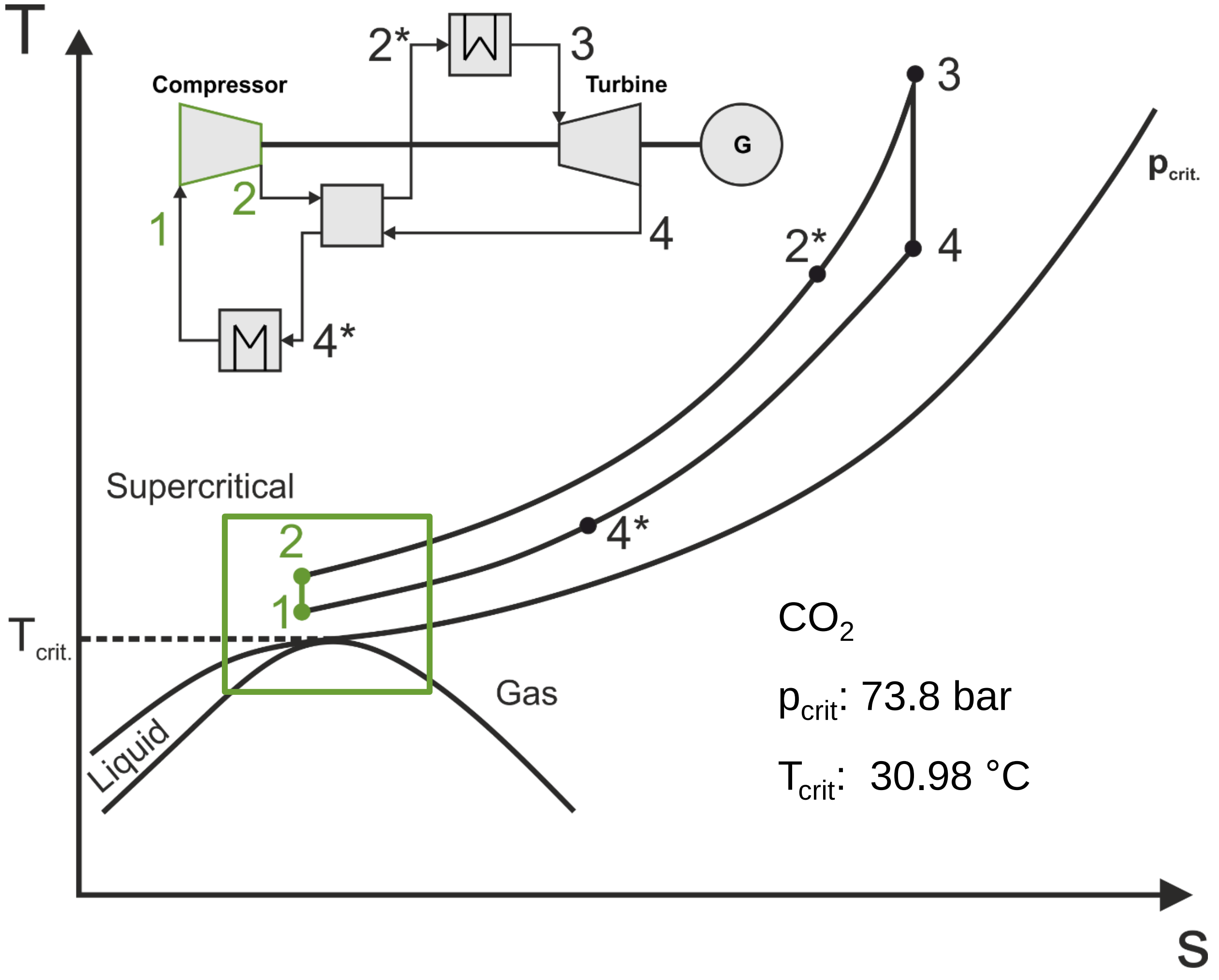
sCO_2-Power Systems

Characteristics

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

Application Areas

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



CO_2

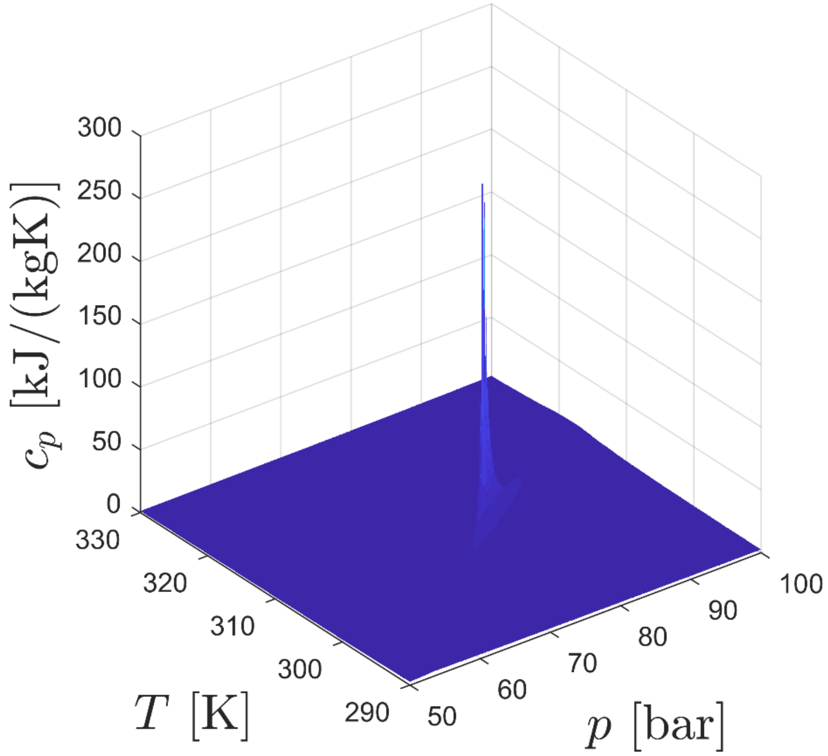
p_{crit}: 73.8 bar

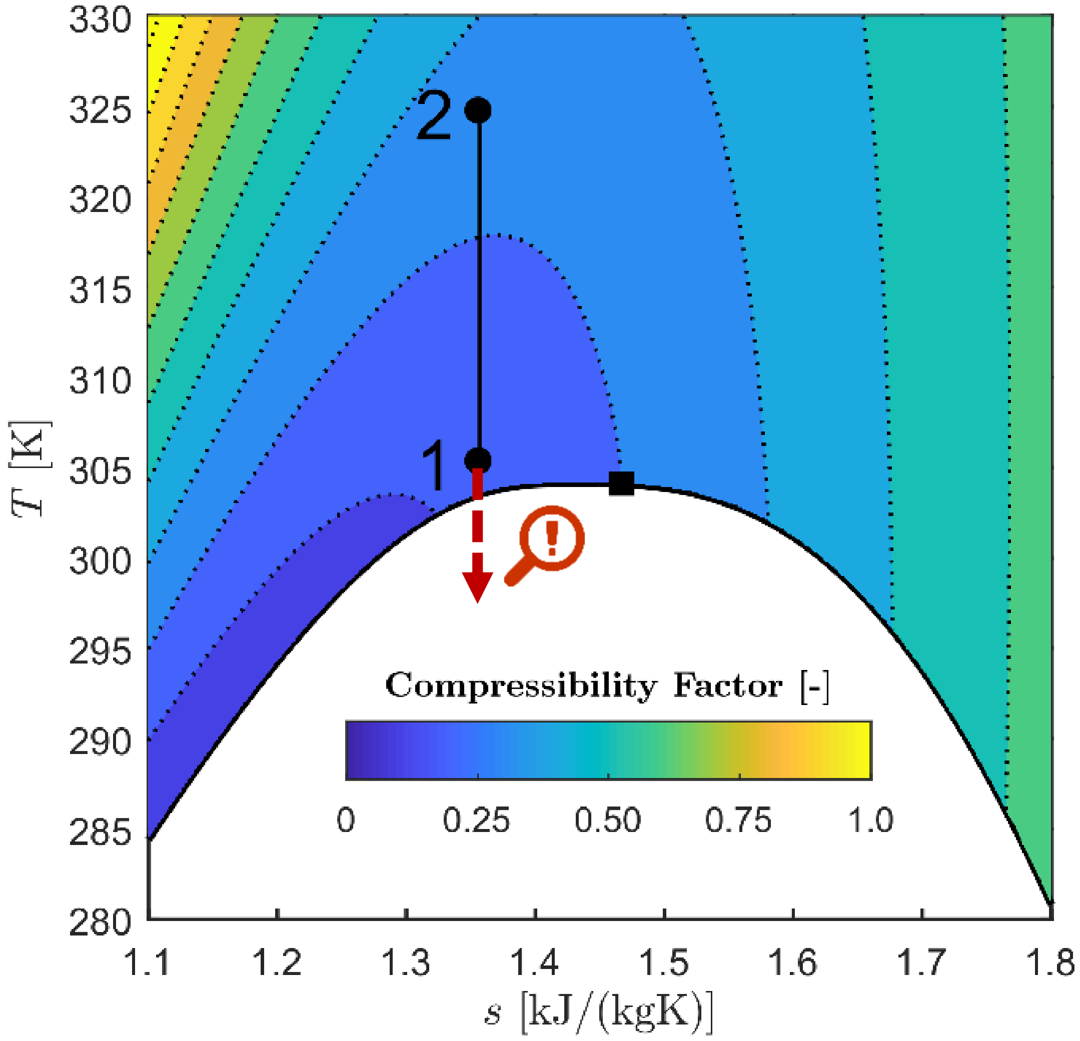
T_{crit}: 30.98 °C

Motivation

Challenges for 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





Motivation

Scope of work

- Extension of the in-house CFD solver to account for thermophysical properties of sCO_2 with high degree of accuracy and numerical stability
  - Span-Wagner multiparameter EOS is too computationally expensive
  - Integration via Spline Based Table Lookup Method [1,2]

- Validation of the CFD framework for sCO_2 compressor performance and flow field assessments
  - Lack of fully documented experimental test cases
  - Investigation of a geometry based on the main dimensions of the SNL main compressor

- Development and validation of a sCO_2 compressor performance meanline analysis tool
  - Further reference for performance assessments
  - Breakdown of individual loss contributions

Outline

1 Motivation

2 Test Case Description

3 Methodology

4 Results

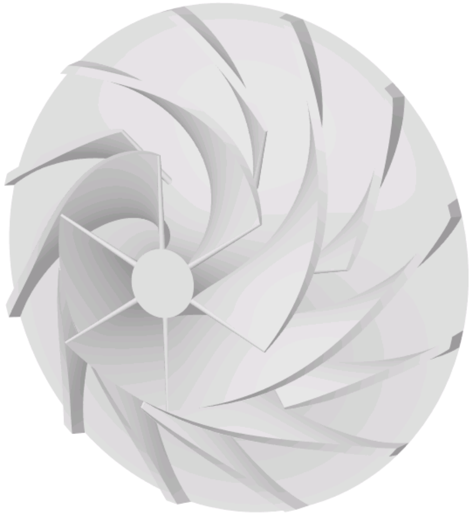
5 Conclusion and Future Work

Test Case Description

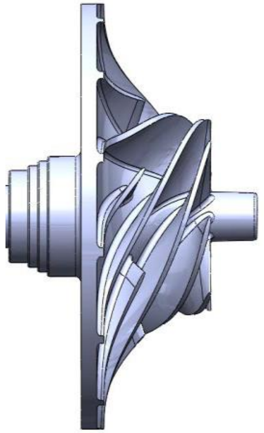
SNL Compressor

- Candidate geometry based on main dimensions of the SNL compression test-loop main compressor
  - Backward swept impeller with splitter blades and a channel diffuser
  - Design specifications:
    50 kWe / 75 krpm / 3,54 kg·s^{-1} / η_{ts}≈ 66% / π = 1,8
    $T_{0,in}/T_c \approx 1.004$, $p_{0,in}/p_c \approx 1.04$
- Restrictions
  - Main dimensions reported partially
  - No blade coordinates accessible
    → Correct reconstruction of blade angle and thickness distribution is not possible
- Simplifications in this preliminary study
  - No tip clearance modeled
  - No diffuser modeled

CAD model of the investigated impeller geometry



$d_2 \approx 37$ mm



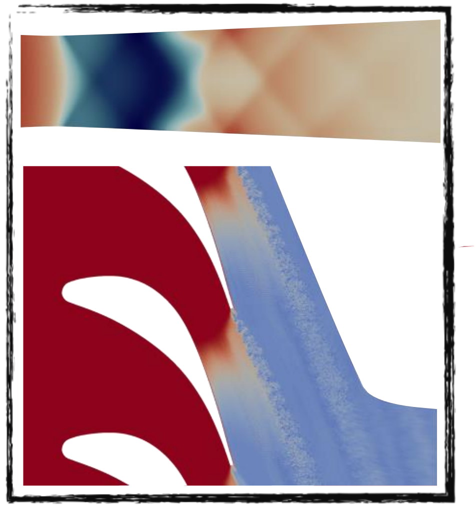
Part drawing and photograph of the SNL main compressor [3]

Methodology

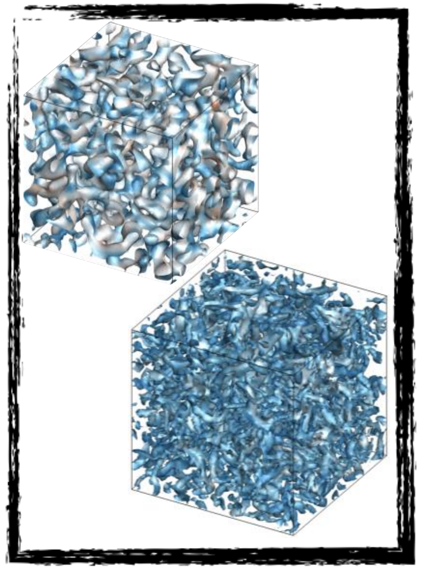
CFD Solver

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

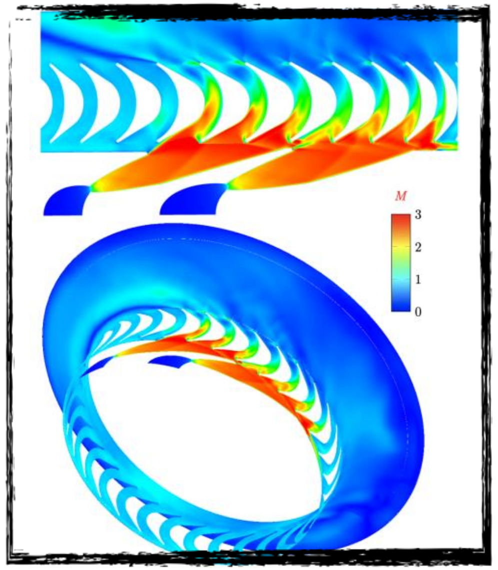
CONDENSING WET STEAM (LES) [5]



DNS/LES



ORC [4]

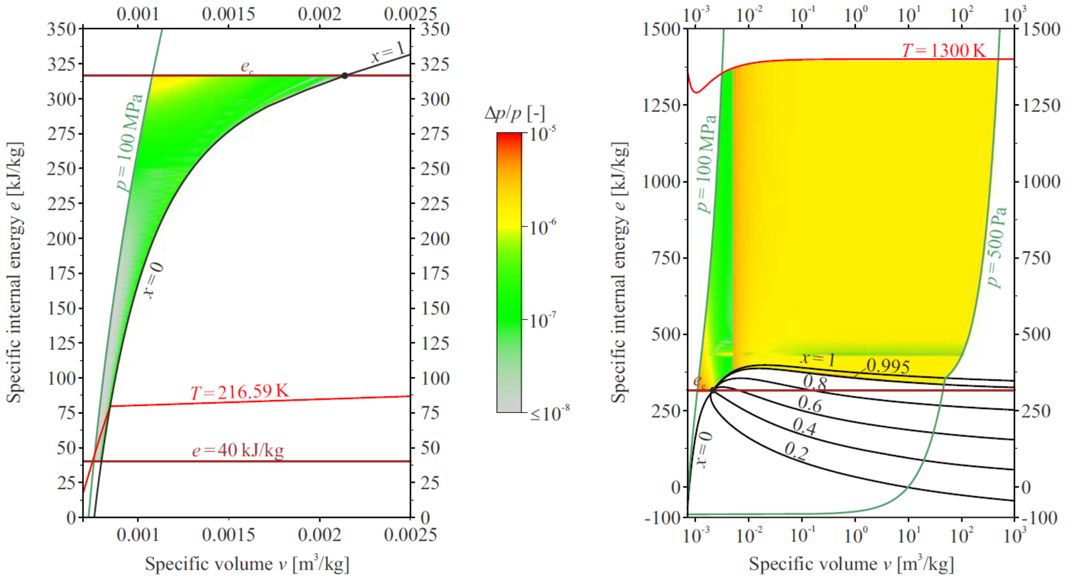


Methodology

Real Gas Property Tabulation

- Spline Based Table Lookup Method (SBTL) [1,2]
  - 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 [6] and correlations for viscosity and thermal conductivity [7,8]
- Perimissible deviations are within uncertainties of the underlying equations/correlations

Permissible deviations of spline-functions (CO_2 application)



[16]

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)
$w(v,e)$		$\lvert\Delta w/w\rvert < 0.001$ %	$\lvert\Delta w/w\rvert < 0.001$ %
$\eta(v,e)$		$\lvert\Delta \eta/\eta\rvert < 0.001$ %	$\lvert\Delta \eta/\eta\rvert < 0.001$ %
$\lambda(v,e)^{a}$		$\lvert\Delta \lambda/\lambda\rvert < 0.001$ %	$\lvert\Delta \lambda/\lambda\rvert < 0.001$ %

[16]

[1] 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.

[2] 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

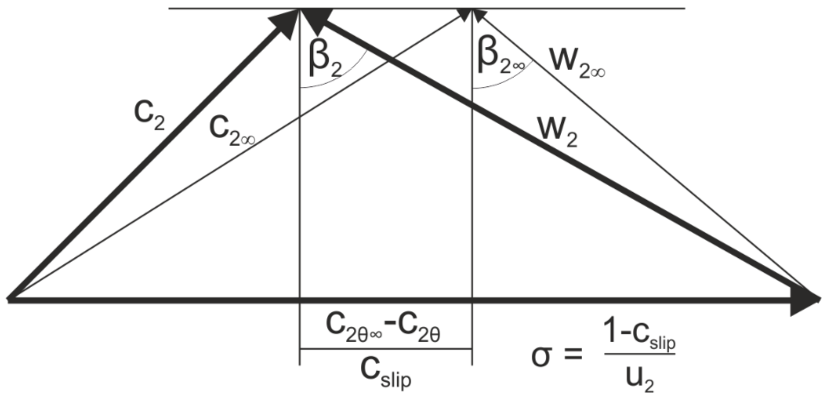
Meanline Analysis Method

- Single-zone modeling approach
- Implemented in PYTHON with direct calls to the CoolProp [9] property library
- Applied loss model set is based on an optimised and validated set of internal and external loss for conventional centrifugal compressors (Oh et al. [10])
- Wiesner slip correlation [11] is applied

$$\sigma = 1 - \frac{\sqrt{\cos\beta_{2,bl}}}{Z_{bl}^{0.7}} \qquad \text{(meridional angle system)}$$

$$W_{Euler} = u_2 c_{2\theta} - u_1 c_{1\theta} = u_2(\sigma u_2 + c_{2m}\tan\beta_{2,bl})$$

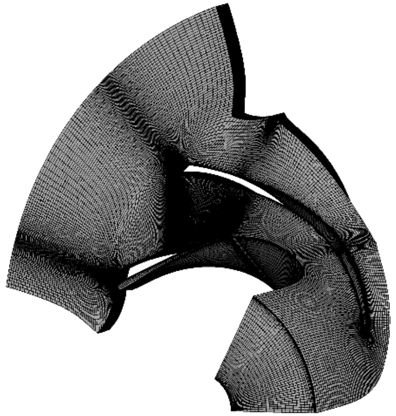
	Loss mechanism	Loss model	Reference
internal	Incidence	$\Delta h_{inc} = \sigma \cdot \frac{\sin^2(\beta_1 - \beta_{1,bl}) w_1^2}{2}$	Conrad et al. [9]
	Blade loading	$\Delta h_{bl} = 0.05 \cdot D_f^2 \cdot u_2^2$	Coppage et al. [10]
	Skin friction	$\Delta h_{sf} = 2c_f \frac{L_{fl}}{d_{hb}} \bar{w}^2$	Jansen [15]
	Clearance	$\Delta h_{cl} = u_2^2 0.6 \frac{\delta}{b_2} \frac{c_{2\theta}}{u_2} \times \sqrt{\frac{4\pi}{b_2 Z_{bl}} \left[\frac{r_{1t}^2 - r_{1h}^2}{(r_2 - r_{1t})(1 + \rho_2/\rho_1)}\right] \frac{c_{2\theta}}{u_2} \frac{c_{1m}}{u_2}}$	Jansen [15]
	Mixing	$\Delta h_{mix} = \frac{1}{2} \frac{c_2^2}{1 + (c_{2\theta}/c_{2m})^2} \cdot \left[\frac{1 - \varepsilon - B}{1 - \varepsilon}\right]$	Johnston & Dean [17]
external	Disk friction	$W_{df} = f_{df} \frac{\bar{\rho} r_2^2 u_2^3}{4\dot{m}}$	Daily & Nece [11] as quoted by Oh et al. [23]
	Recirculation	$W_{rc} = 8 \cdot 10^{-5} \sinh(3.5\alpha_2^3) D_f^2 u_2^2$	Oh et al. [23]
	Leakage	$W_{lk} = \frac{\dot{m}_{cl} u_{cl} u_2}{2\dot{m}}$	Aungier [5]

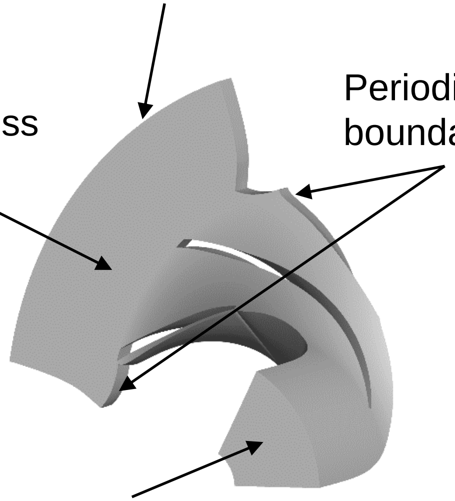


Methodology

Numerical Setup

- Steady state RANS simulations
  - Second order AUSM+scheme [12]
  - Implicit LUSGS scheme
- Spalart-Allmaras turbulence model [13]
- Homogenous equilibrium mixture (HEM)
- Block structured mesh
  - No wall functions: y+ < 5
  - ≈ 1.7 mio. cells for single main + splitter blade
- Single domain, no interface





Outlet: static pressure

Vaneless space

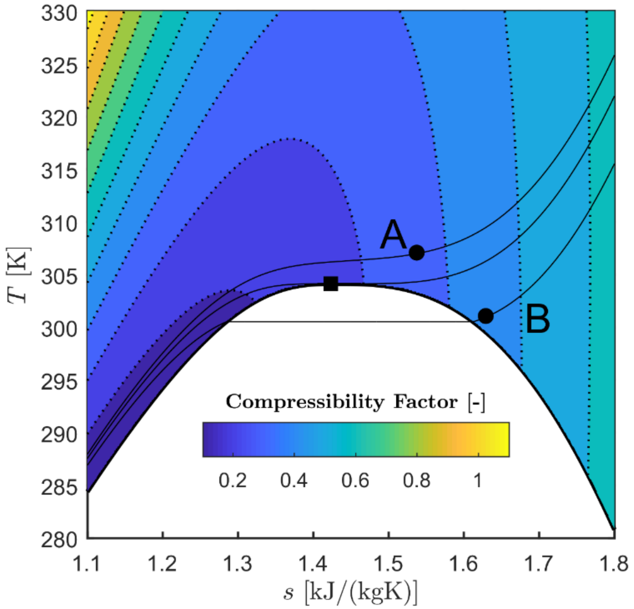
Periodic boundaries

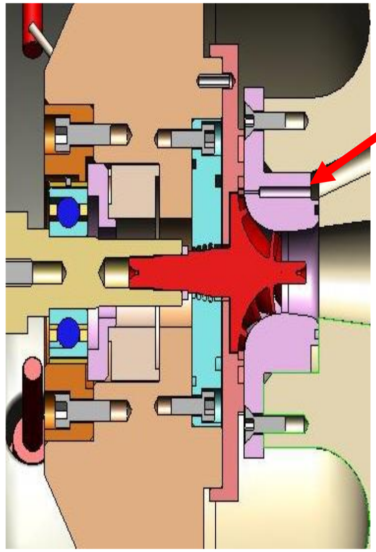
Inlet:
- Total temperature
- Total pressure
- Uniform and normal flow

Compressor Performance

Investigated Compressor Operating Conditions

- Based on experimental campaigns of Wright et al. [3,14] and Fuller & Eisemann [15]
  - A: Near-Critical Inlet State
    77.50 bar, 307 K
  - B: Gaseous Inlet State,
    Potentially relevant during cycle startups
    67.93 bar, 301 K
- 50 krpm speedline calculation (off-design)
  → most data available
- 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



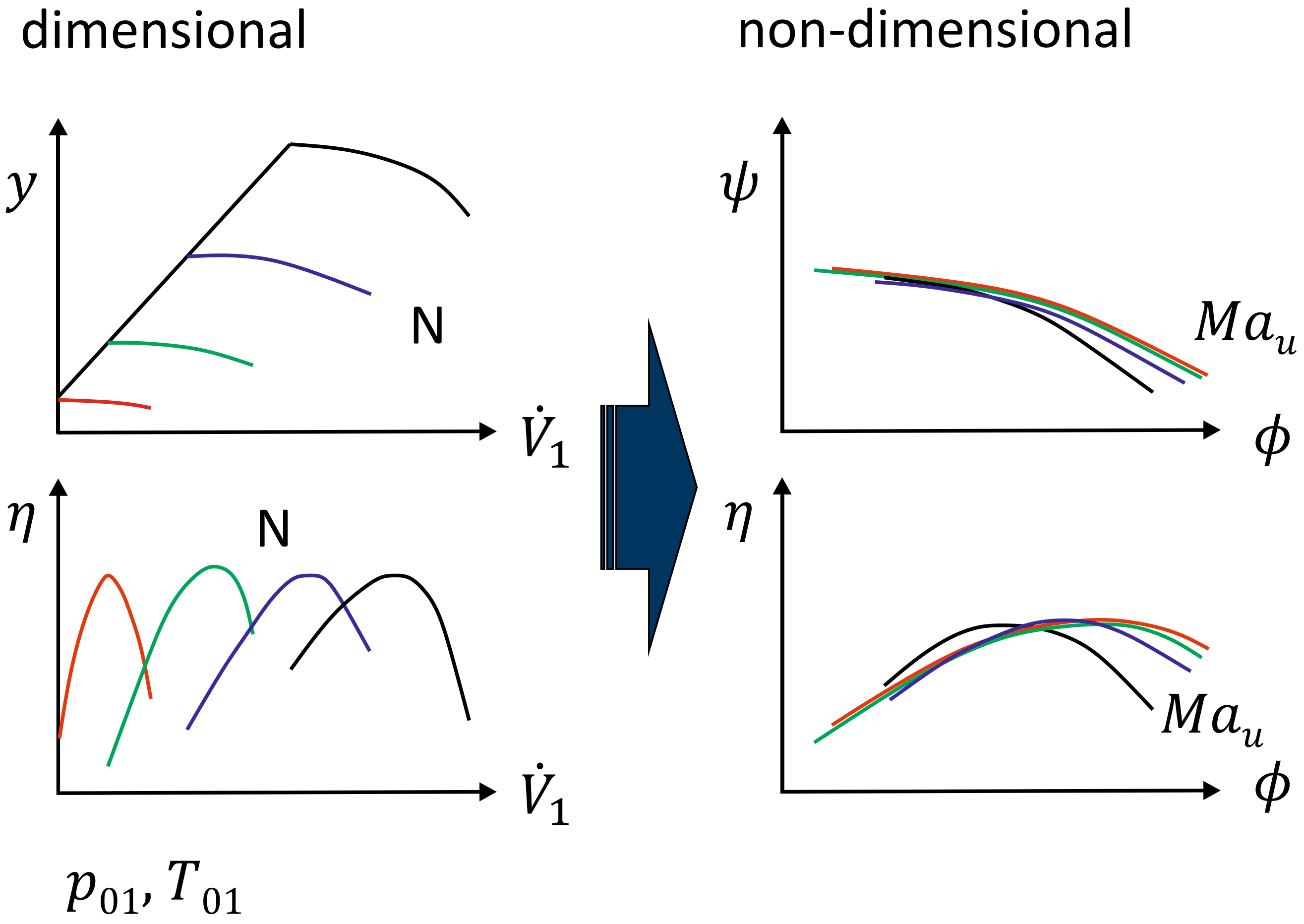


Static pressure tap

[3]

Compressor Performance

Performance Assessment



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

$$\psi = \frac{h_{2s} - h_{01}}{u_2^2}$$ Head Coefficient

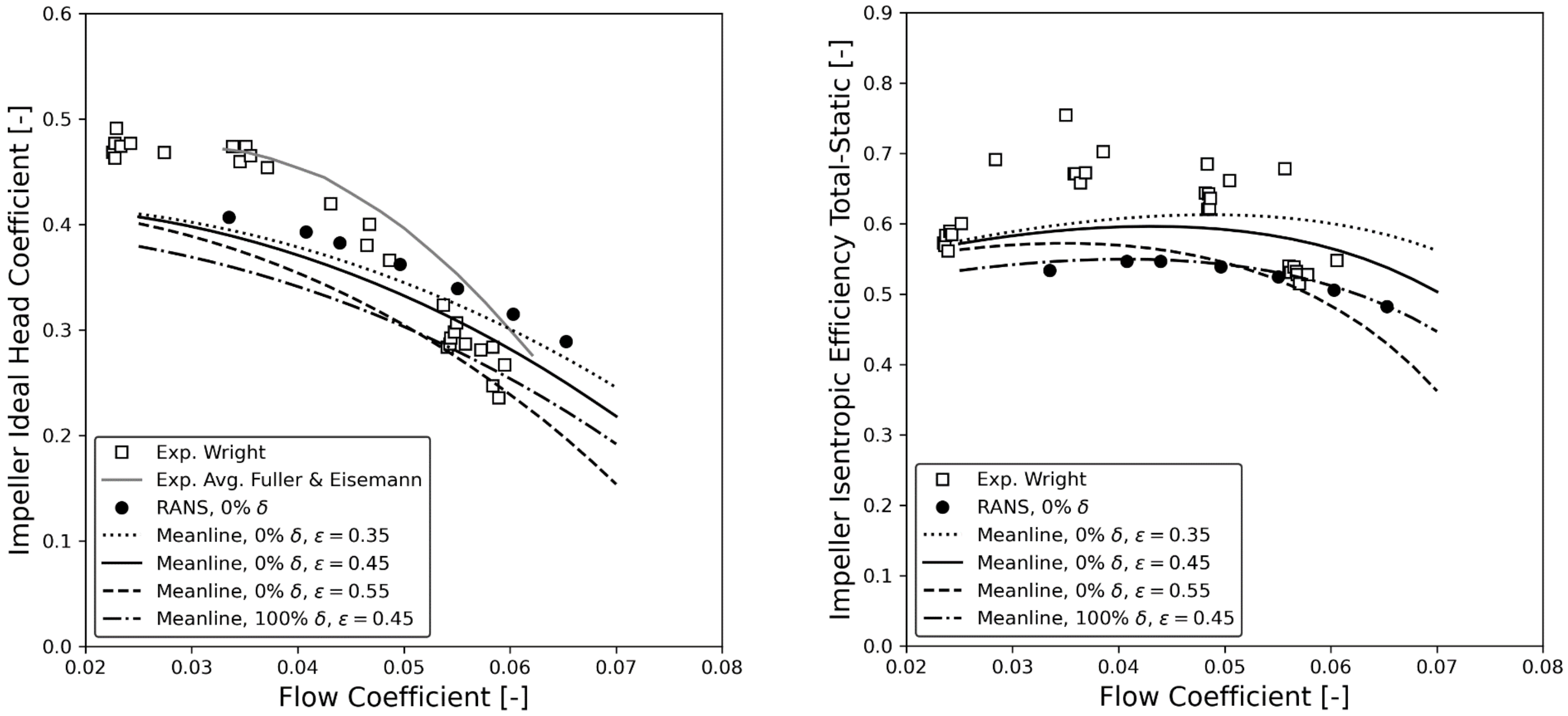
$$\eta_s = \frac{h_{2s} - h_{01}}{h_{02} - h_{01}}$$ Isentropic Efficiency

Compressor Performance

Compressor Performance

State A: Near Critical Operation

- RANS
  - Flatter head characteristic
  - Reduced efficiencies
  - Surge comparable
- Meanline
  - Slope of head curve shows better agreement with RANS
  - Sensitive towards inputs of the parameter ε for high flow coefficients
  - Consideration of tip clearance: 7-14 % decreased head generation,
    4-6 percentage points decreased efficiency



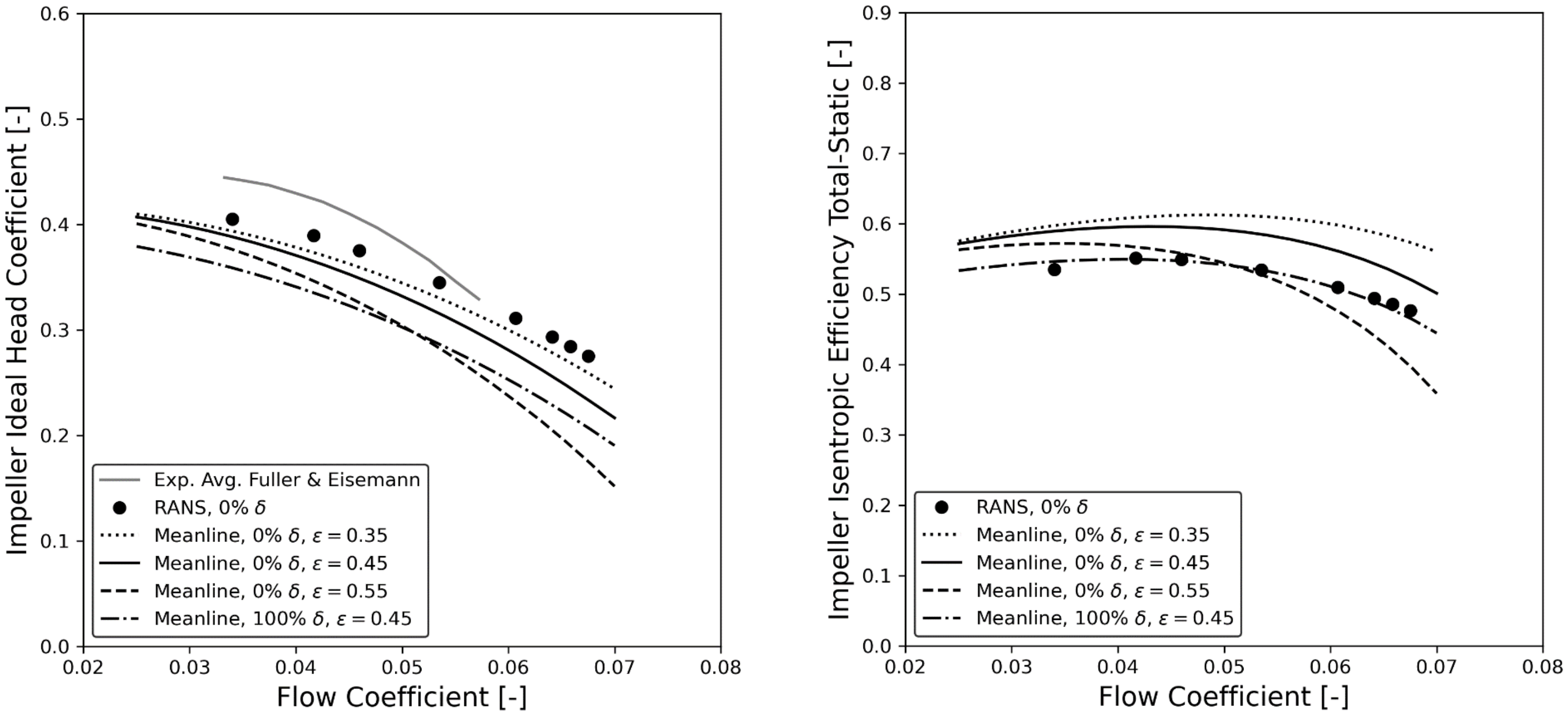
ε: fraction of blade to blade space occupied by the wake
(Mixing loss model of Johnston & Dean)

Compressor Performance

Compressor Performance

State B: Gaseous Operation

- Almost no difference compared to state A
  → High degree of machine similitude



ε: fraction of blade to blade space occupied by the wake
(Mixing loss model of Johnston & Dean)

Compressor Performance

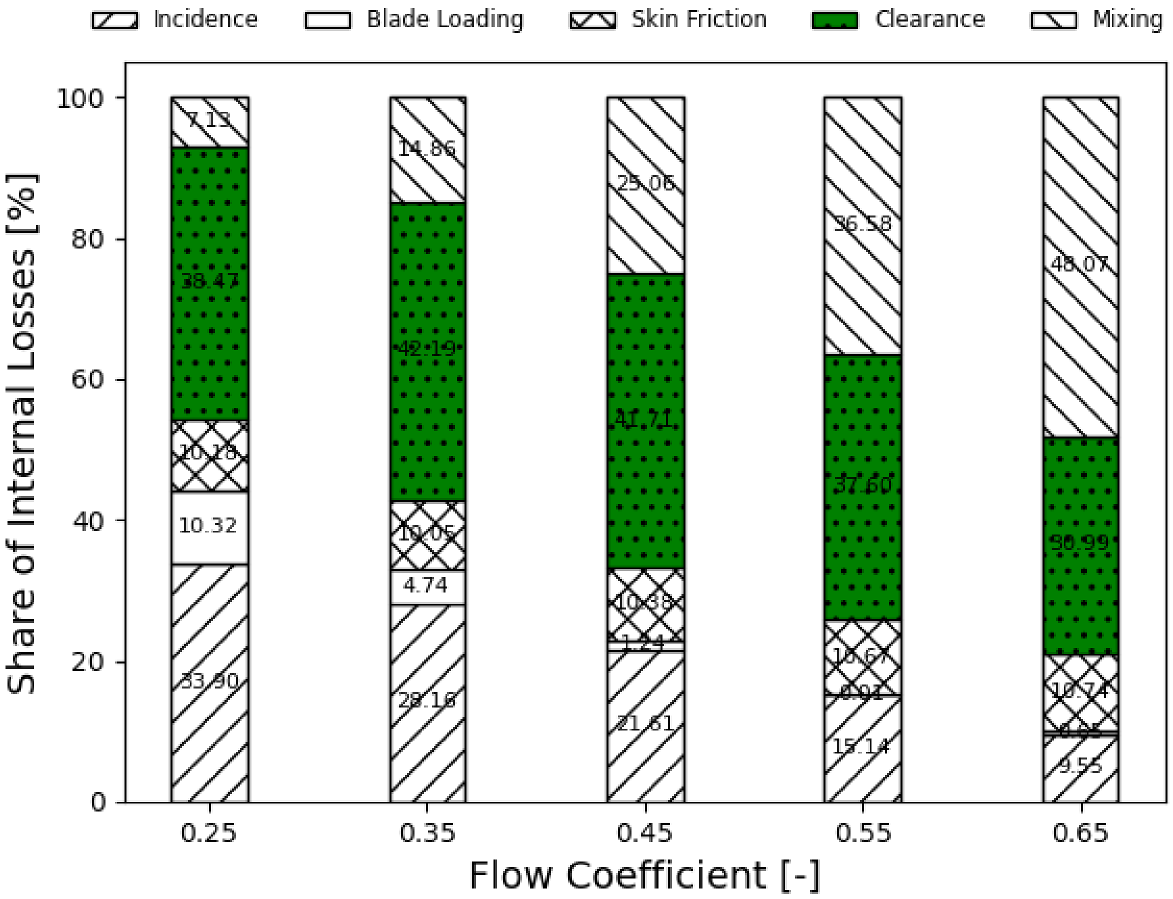
Meanline Loss Distribution

- Clearance loss with significant share over the entire flow range (≈ 40 %)

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

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

State A



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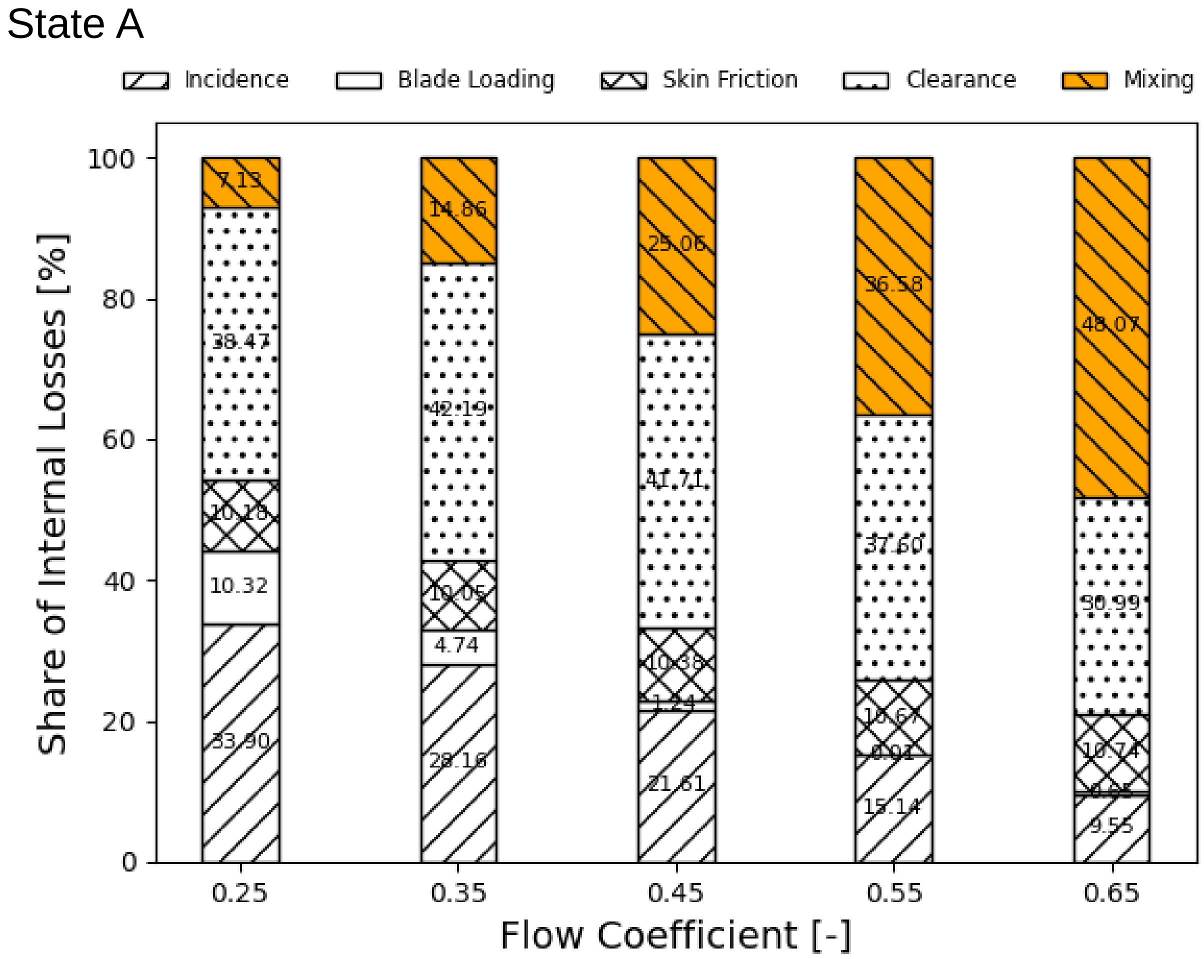
- Wake mixing losses dominant at high flow coefficients
  - Explains high sensitivity of ε in performance curve derivation



Compressor Performance

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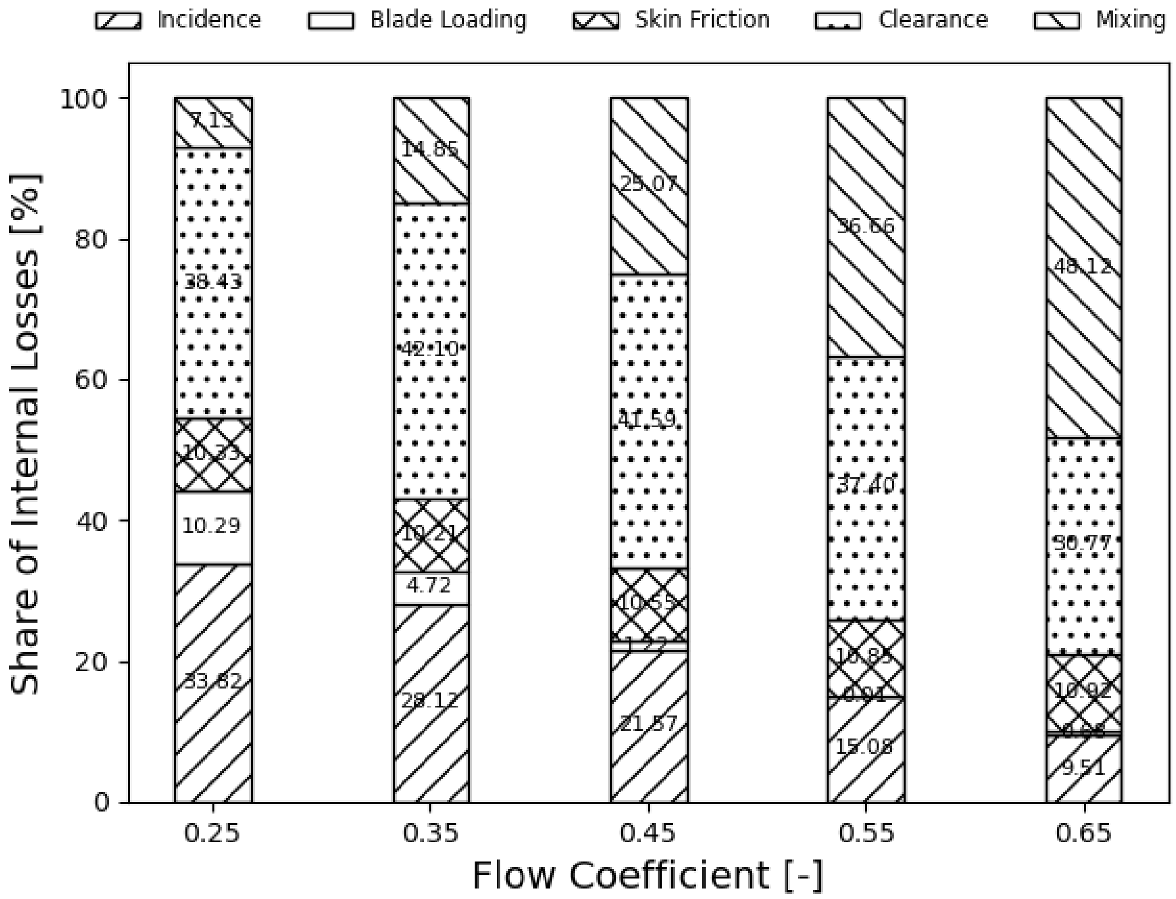
  Eckardt Impeller: $\frac{\delta}{d_2} \approx 0.001$

- Wake mixing losses dominant at high flow coefficients
  - Explains high sensitivity of ε in performance curve derivation

- Shares at state B almost identical due to similitude of velocity triangles

State B



Flow Field Analysis

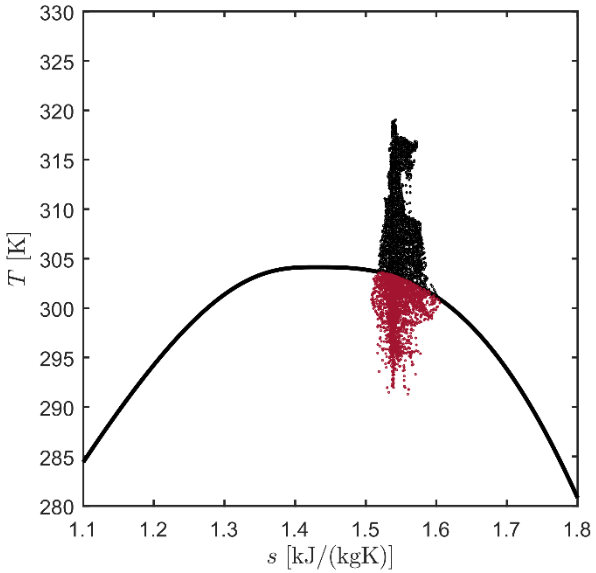
Vapour-Liquid Region

- Points within the vapour-liquid region detected for all simulations
- Located near the impeller leading edges
- Caused by flow acceleration at the suction side
- Small volume fraction of entire domain
  - State A simulations: < 0.02 %
  - State B simulations: < 1.1 % (closer location to the VL-region)

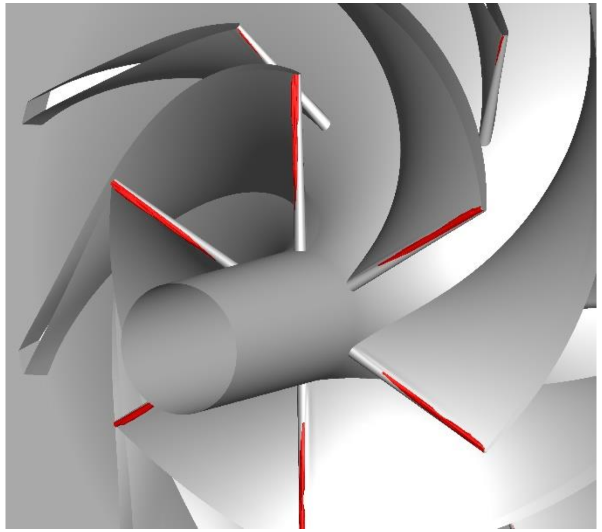
Current limitations:

- Simulations do not account for metastable states
- Non-equilibrium condensation is not modeled

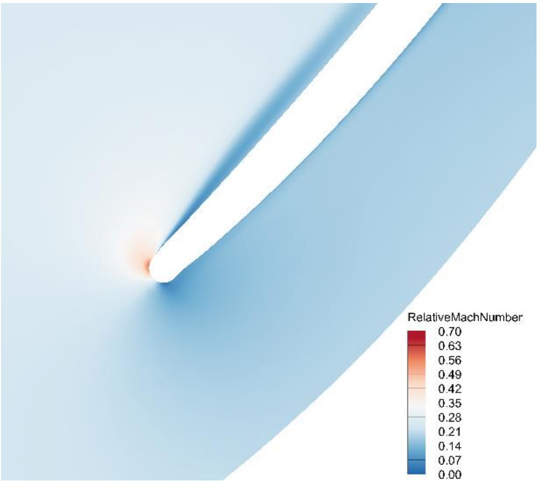
scatter plot of solution domain



isocontours of points within the VL-region



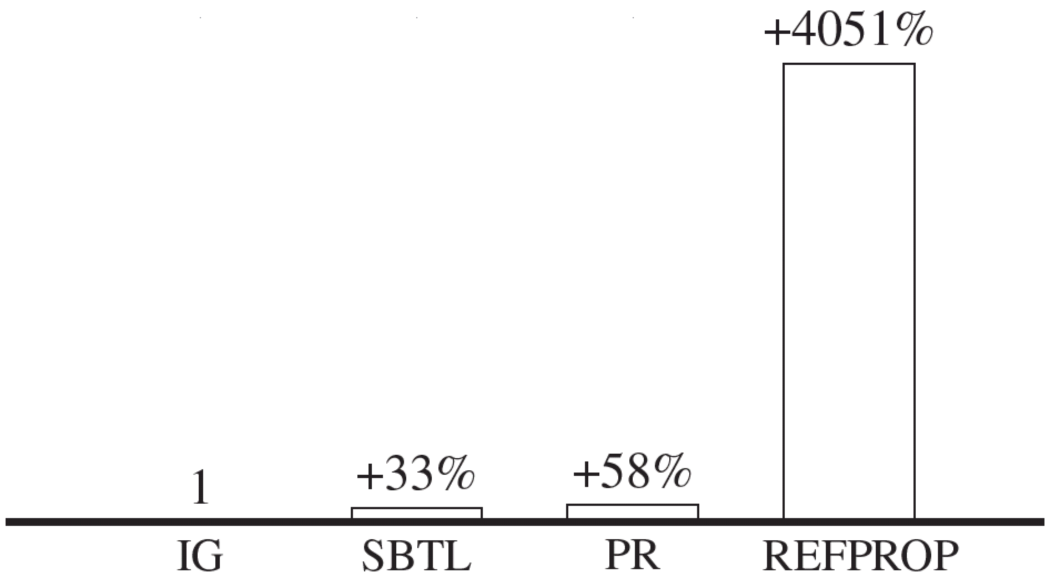
contours of relative Mach number at 75 % span



Evaluation of computational speed

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)



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Conclusion and Future Work

Conclusion

- Reasonable performance metrics are derived for two operating states despite approximations of the candidate compressor geometry
- High degree of machine similitude observed for both operating states
  → Finding suggests that non-dimensional sCO2 performance testing could be numerically and practically conducted at inlet states with less pronounced gradients in thermophysical properties
- Compressor operation close to the VL-region might potentially lead to condensation of a small volumetric region
- Meanline loss distributions indicate tip clearance as a dominant loss contributing factor over the entire operating range
- CFD Framework comprising the SBTL library allows for accurate calculations within the range of uncertainties of the EOS at comparatively low computational overhead (33 % compared to IG)

Future Work

- Integration of metastables states and assessment of non-equilibrium condensation
- Extension of the geometry to account for the channel diffuser

THANK YOU

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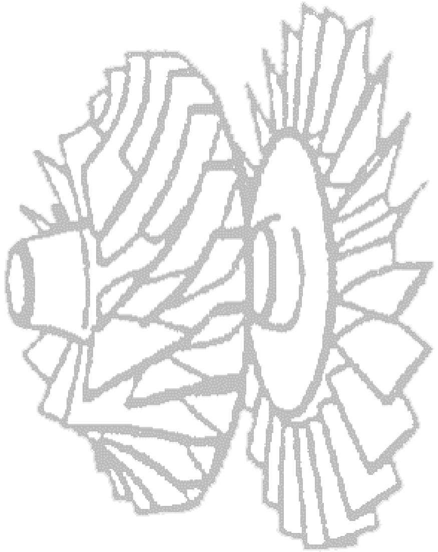

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