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

Renan Emre Karaefe¹, Pascal Post¹, Marwick Sembritzky¹, Andreas Schramm¹, Matthias Kunick², Uwe Gampe³, Francesca di Mare¹

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

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

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

![T-S diagram showing CO$_2$ cycle with critical points $p_{\text{crit}}$: 73.8 bar and $T_{\text{crit}}$: 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:
    - $50 \text{kWe} / 75 \text{krpm} / 3.54 \text{kg} \cdot \text{s}^{-1} / \eta_{ts} \approx 66\% / \pi = 1.8$
    - $T_{0,\text{in}}/T_c \approx 1.004, p_{0,\text{in}}/p_c \approx 1.04$

- 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

$d_2 \approx 37 \text{ mm}$

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]

- Permissible deviations are within uncertainties of the underlying equations/correlations


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

\[ \sigma = 1 - \frac{\sqrt{\cos \beta_{2,bl}}}{Z_{bl}^{(1)}} \] (meridional angle system)

\[ W_{Euler} = u_2 c_{2\theta} - u_1 c_{1\theta} = u_2 (\sigma u_2 + c_{2m} \tan \beta_{2,bl}) \]
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: $y+ < 5$
  - $\approx 1.7$ mio. cells for single main + splitter blade
- Single domain, no interface

Outlet: static pressure
Inlet:
- Total temperature
- Total pressure
- Uniform and normal flow
Vaneless space
Periodic boundaries
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
Compressor Performance

Performance Assessment

**Dimensional**

- \( \eta \) vs. \( \dot{V}_1 \)
- \( \eta \) vs. \( P_{01}, T_{01} \)

**Non-Dimensional**

- \( \psi \) vs. \( \phi \)
- \( \eta \) vs. \( \phi \)

\[
\phi = \frac{4\dot{V}_1}{\pi d^2 u_2} \quad \text{Flow Coefficient}
\]

\[
\psi = \frac{h_{2s} - h_{01}}{u_2^2} \quad \text{Head Coefficient}
\]

\[
\eta_s = \frac{h_{2s} - h_{01}}{h_{02} - h_{01}} \quad \text{Isentropic Efficiency}
\]
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 $\varepsilon$ for high flow coefficients
  - Consideration of tip clearance: 7-14 % decreased head generation, 4-6 percentage points decreased efficiency

$\varepsilon$: fraction of blade to blade space occupied by the wake
(Mixing loss model of Johnston & Dean)
Compressor Performance

State B: Gaseous Operation

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

\[ \varepsilon: \text{fraction of blade to blade space occupied by the wake} \]

(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: $\frac{\delta}{d_2} \approx 0.001$
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: \( \frac{\delta}{d_2} \approx 0.001 \)

- Wake mixing losses dominant at high flow coefficients
  - Explains high sensitivity of \( \varepsilon \) in performance curve derivation
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: \( \frac{\delta}{d_2} \approx 0.001 \)

- Wake mixing losses dominant at high flow coefficients
  
  • Explains high sensitivity of \( \varepsilon \) in performance curve derivation

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

![Diagram showing share of internal losses in State B for different flow coefficients]
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
### 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)
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

Renan Emre Karaefe

emre.karaefe@rub.de
References


