INVISCID STATOR/ROTOR INTERACTION OF A SINGLE STAGE HIGH EXPANSION RATIO ORC TURBINE

2nd International Seminar on ORC Power Systems

E. Rinaldi, A. Buonocore, R. Pecnik, P. Colonna
Delft University of Technology

TU Delft

Outline

TUDelft

TU Delft

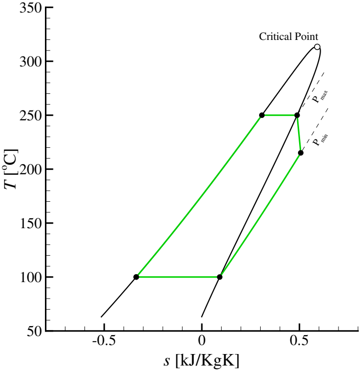
Motivation

Preliminary design: standard tools

Considerable improvement of non-conventional machines
$\Longrightarrow$ accurate and reliable CFD

Challenges:

- High expansion ratio
  $\Longrightarrow$ supersonic flows
- Detailed unsteady simulations
- Expansion in the *dense gas* region
- Accurate thermophysical description of the fluid



Objectives

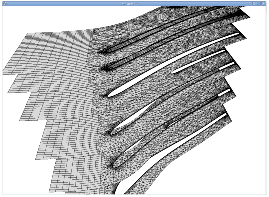
- Improve the CFD predictive capability:
  - High quality mesh generation
  - RANS equations for real fluids
  - Unsteady simulations (stator/rotor interaction)
  - Reduce the computational cost
- Analysis of existing designs:
  - On design conditions
  - Off design conditions (variable input)
- Main objective: improve the turbomachinery performance
  - Automatic shape optimization

1. Motivation
2. Methodology
3. Results
4. Conclusions

Mesh generation

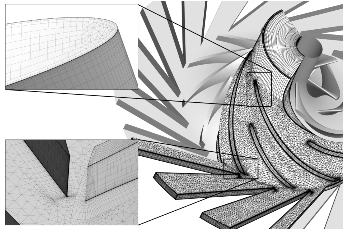
Motivation:

- Accurate results need high quality mesh
- In-house tools to be coupled for optimization



Features:

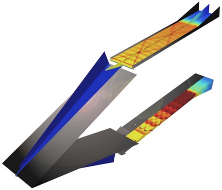
- Quadrilateral and triangular elements
- OpenGL visualization
- IO interface to FLUENT ***neu*** and ***msh*** format
- Coordinate transformation
- Fully automated

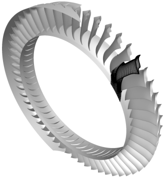


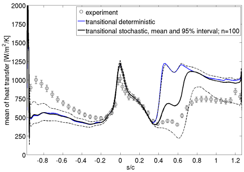
TU Delft

CFD Code

- SU-Joe (Stanford University)
- Cell centered finite volume discretization
- Second order space (least-squares gradient) and time accuracy (Runge–Kutta, BDF2)
- Highly optimized and scalable for HPC (up to 4000 cores)
- Mixing plane, sliding interface
- Supports UQ methods
- Validation: scramjet engines, compressor stages P&W turbofan
- Real gas EoS (tables)

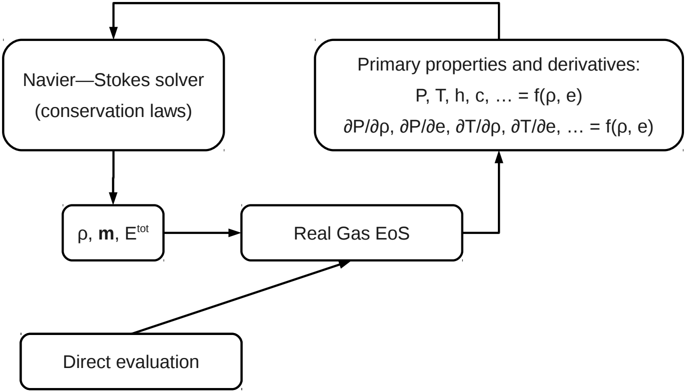




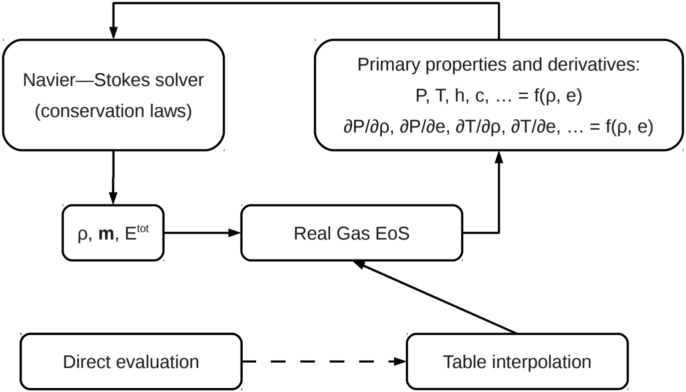


Pecnik, R., *et al.*, *AIAA Journal*, 2012, *50*, 1717–1732

Real gas solver



Real gas solver



Interpolation accuracy

— bilinear

-·- least-squares gradient

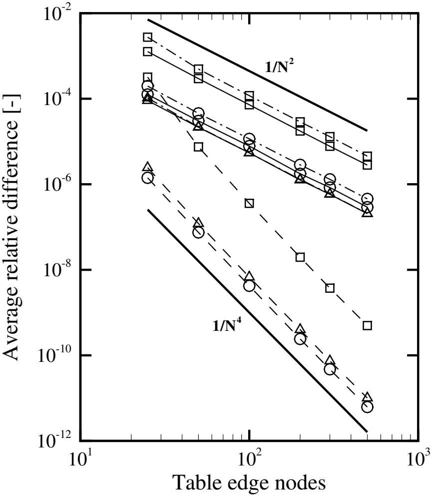
--- polynomial

△ speed of sound

□ c_P

○ pressure

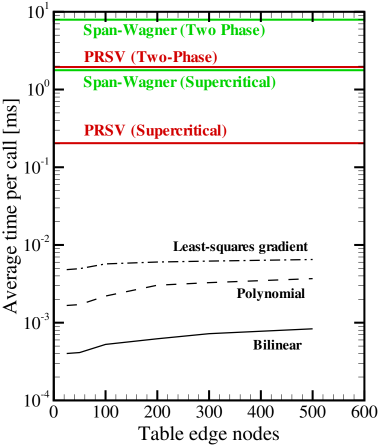
- Polynomial: 4th order convergence
- Max interpolation error 100x100 table:
  - ≈ 0.01% bilinear/gradient
  - ≈ 0.0001% polynomial



TUDelft

Computational cost

- SW 1 order of magnitude more expensive than PRSV
- EoS evaluation cost depends on the input
- Tables: max gain up to 4 orders of magnitude



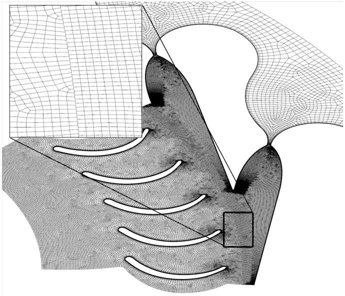
ORC Turbine

Cycle:

- Waste heat: $T > 350°$C, 450-900 kW_{th}
- Power output: 60-165 kW_e
- Working fluid: Toluene

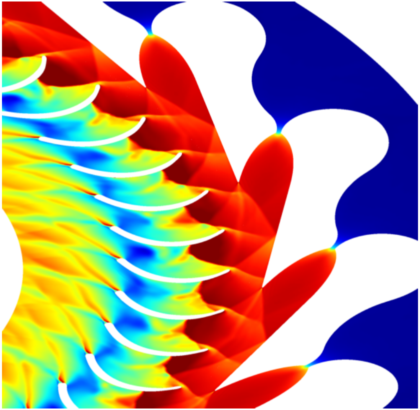
Turbine:

- Radial, single stage low-reaction
- High pressure ratio ($P_{in}/P_{out} > 100$)
- Inlet in the dense gas region
- Rotational speed (18-28 krpm)

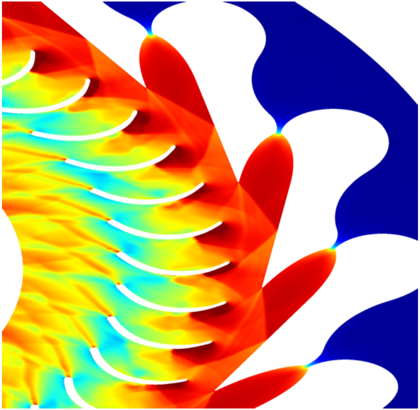


TUDelft

Mach number

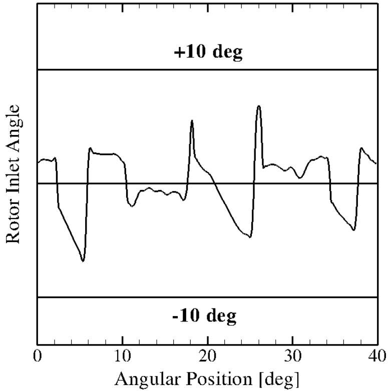


Low rotational speed

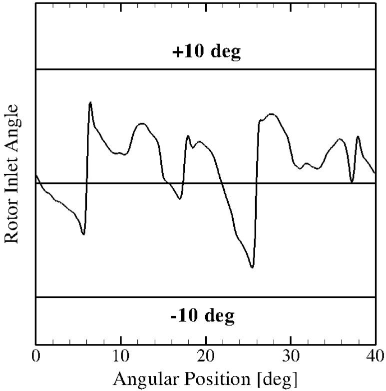


High rotational speed

Rotor inlet angle



Low rotational speed



High rotational speed

TU Delft

TU Delft

Conclusions

- Methodology for accurate real gas simulations
    - Automated meshing tool
    - Real gas Navier–Stokes solver
    - Accurate and efficient properties evaluation
    - Unsteady simulation capability
- Analysis of a high expansion ratio ORC turbine
    - Unsteady stator/rotor interaction
    - Highly supersonic flow
    - Complex shock/shock interaction/reflection

Future work

- Experimental data (mini ORC test bench @TUDelft)
- Three dimensional viscous simulation
- Design improvement (numerical optimization)

Thank you for your attention!

Questions?

TUDelft