THREE-DIMENSIONAL RANS SIMULATION OF A HIGH-SPEED ORGANIC RANKINE CYCLE TURBINE

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Outline

- Introduction: ORC turbines
- Fluid dynamic analysis of ORC turbines
- Example and results
- Possible design improvements
- Outlook and conclusions

Advantages of organic fluid for turbine

Optimal turbine for:

- low capacity (few kW_e to 1 – 2 MW_e)
- low T heat source (150 – 450°C)

Example for heat source of T=305 °C:

		Water	Toluene	MDM
M	[g/mol]	18	92	236
Δh_{turb}	[kJ/kg K]	590	130	60
$\dot{V}_{turb\ inlet}$	[m³/s]	0.01	0.03	0.06

Organic fluids:

Lower Δh_{turb} → fewer stages → **lower cost**
→ **lower rpm**

Higher $\dot{V}$ → lower D_{spec} → **higher efficiency**

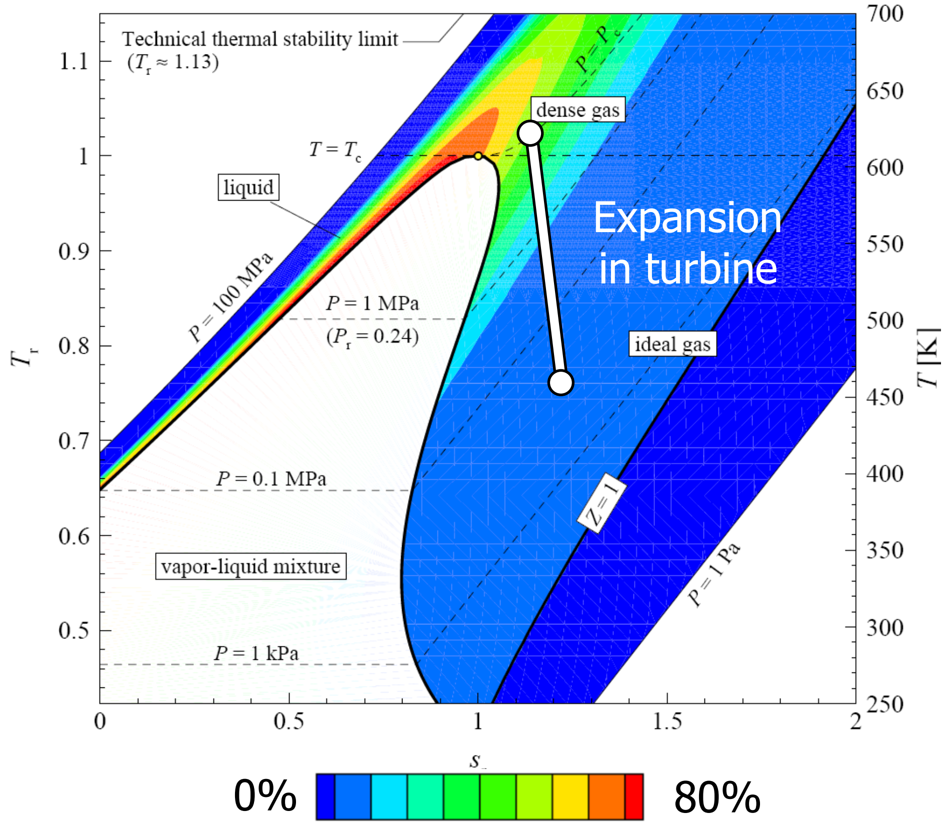
Advantages of organic fluid for turbine

Optimal turbine for:

- low capacity (few kW_e to 1 – 2 MW_e)
- low T heat source (150 – 450°C)

- Select optimal fluid for given power level
- High efficiency turbine ⇨ high efficiency cycle (20% at 325°C TIT)
- Good part-load efficiency
- Dry expansion
- Simple configuration
- Lubricant

Flow analysis/design of ORC turbines



Volumetric deviation from simple ideal gas law in T-s diagram of an organic fluid

- Expansion in dense-gas region
  - → *Accurate thermophysical properties needed*
- Low specific enthalpy drop ($\Delta h_{turbine}$)
  - → High expansion ratio
  - ↓ *Supersonic flow, compression shocks possible*

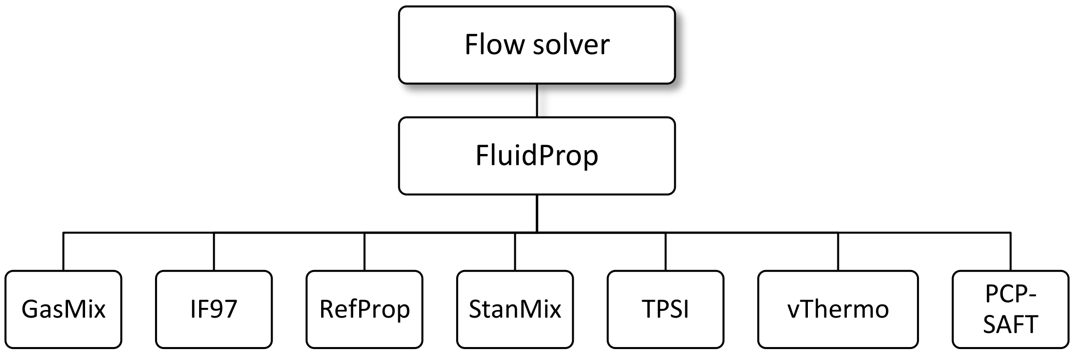
Differences due to (inaccurate) models

Example for a simulated expansion in an ORC stator:

	Flow solvers	Turbulence models	Accurate thermophysical models	Ideal gas law
Mass flow	2%	1%	1%	15%
Efficiency	8%	2%	5%	n.a.
Oulet velocity	3%	1%	0%	50%
Outlet flow angle	2°	1°	0°	2°
Specific work	n.a.	n.a.	6%	n.a.

Coupling with accurate properties

- Options:
  1. directly with accurate thermodynamic models
     e.g., via FluidProp (www.fluidprop.com)



  2. with polynomials fitted to tables
  3. interpolated from look-up tables containing property values

- Accuracy comes at higher computational cost

Progress in ORC turbine design

- Preliminary design / dimensioning:

  based on empirical relations for low-expansion-ratio turbines

- Fluid dynamic design of nozzle/blade shape:

Simpler approach	Nowadays possible
• Inviscid flow solver • Approximate thermodynamic model • 2D • Stator only	• Viscous turbulent solver • Highly accurate multiparameter equations of state • 3D • Complete turbine

3D turbulent RANS simulation of ORC turbine

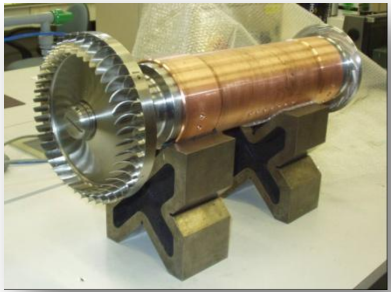
An example

ORC:

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

Turbine:

- Single-stage radial low-reaction turbine
- High pressure ratio ($P_{in}/P_{out}>100$),
- Inlet in dense gas region
  (40% volumetric deviation from ideal gas)
- High rotational speed (18000 - 28000 rpm)



3D turbulent RANS simulation of ORC turbine

Steps towards current methodology

1	Euler	2D*	stator
2	Euler	3D	stator
3	Euler	Throughflow	stator-rotor
4	RANS	2D*	stator
5	RANS	3D	stator
6	RANS	3D	stator-rotor-diffuser

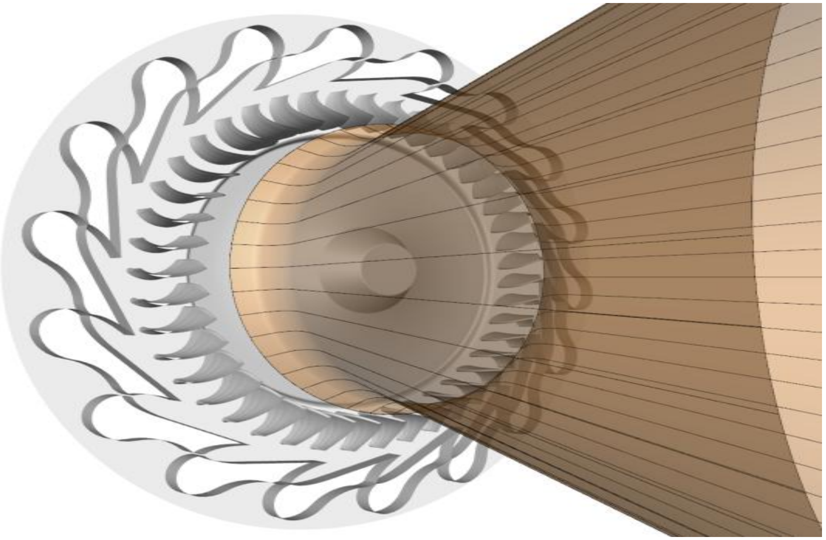
*If geometrically allowable

3D turbulent RANS simulation of ORC turbine

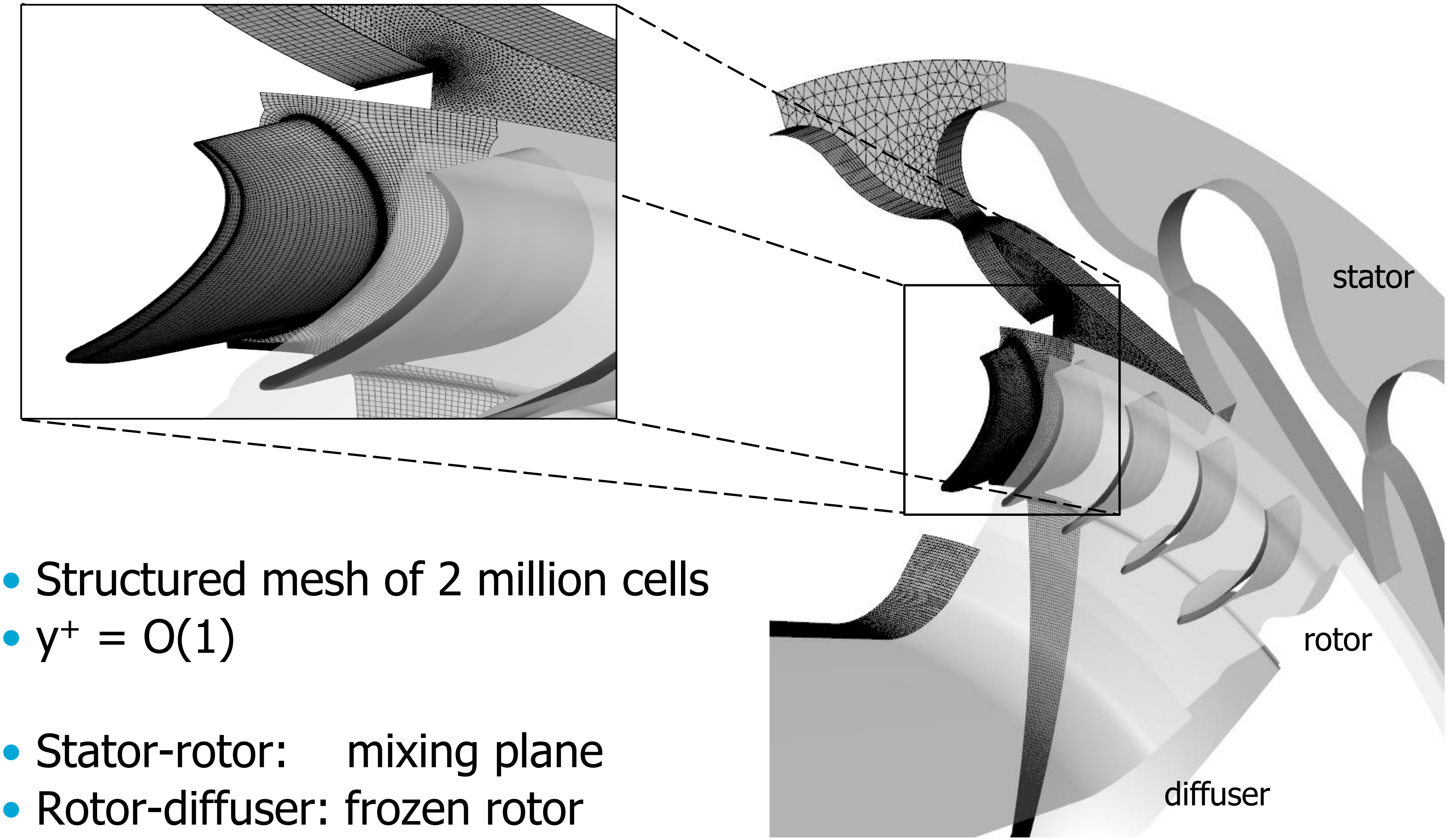
Modeling approach

- RANS
- Look-up table based on highly accurate NIST RefProp multiparameter equation of state
- Shear Stress Transport k - ω turbulence model
- Adiabatic, steady-state flow
- Ansys CFX 13

- Stator, rotor and diffuser



Mesh

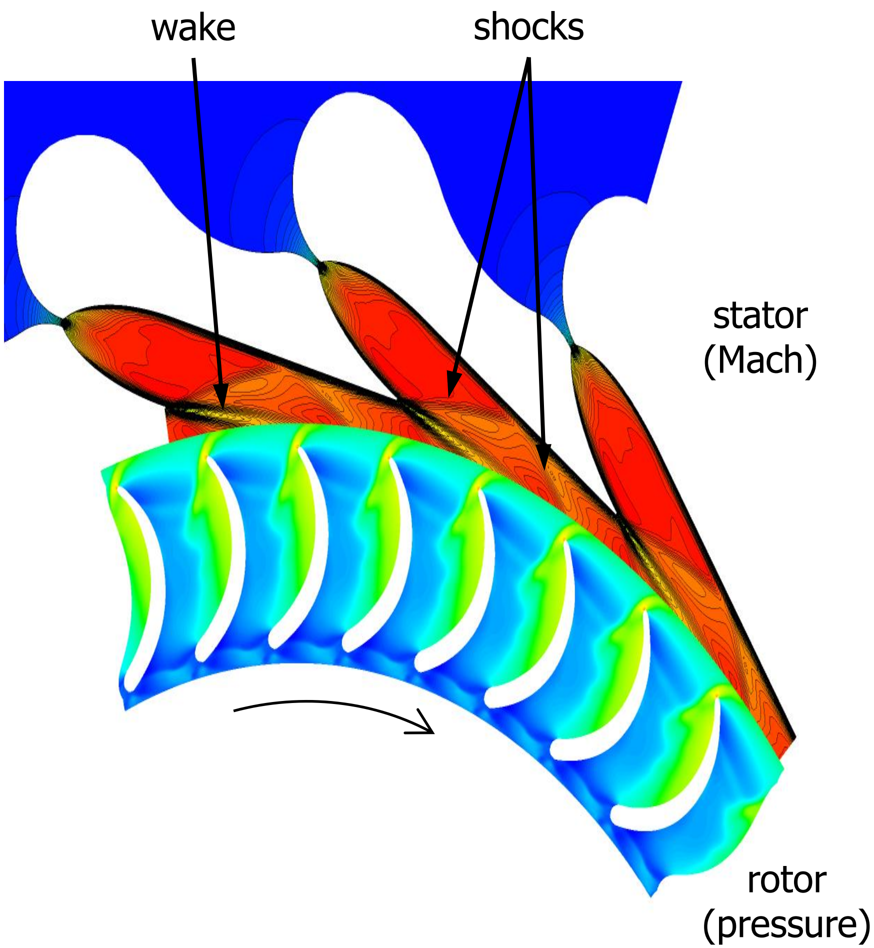


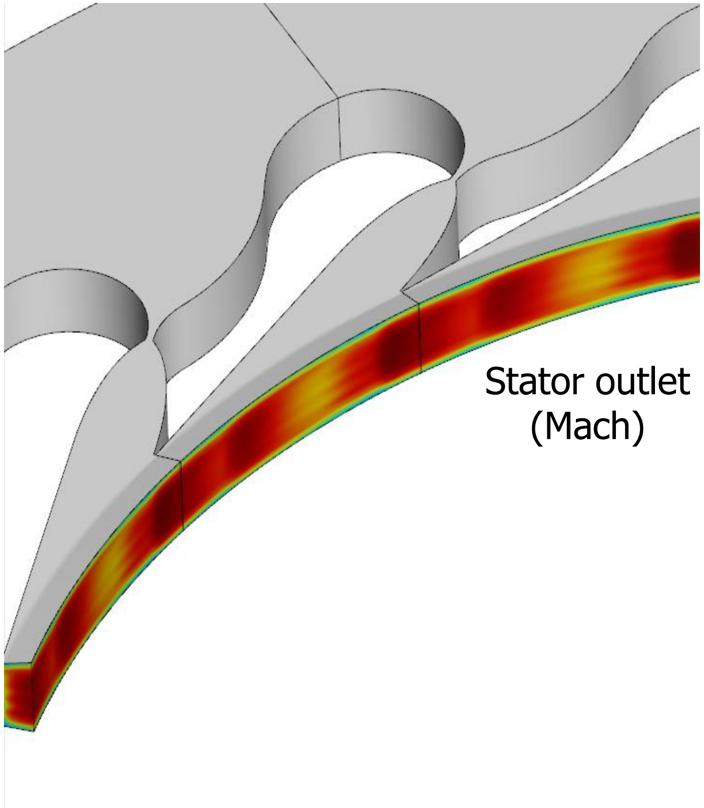
- Structured mesh of 2 million cells
- $y^+ = O(1)$

- Stator-rotor: mixing plane
- Rotor-diffuser: frozen rotor

Results

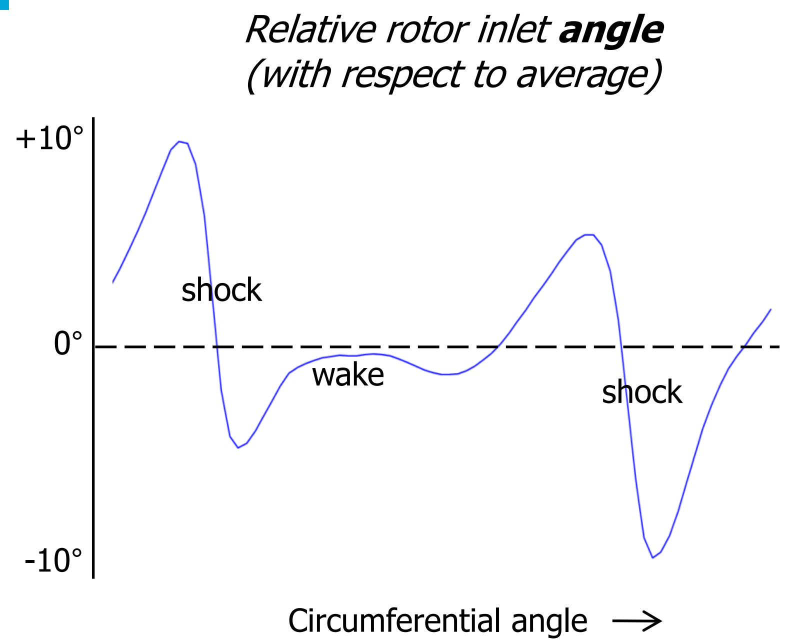
Stator-rotor

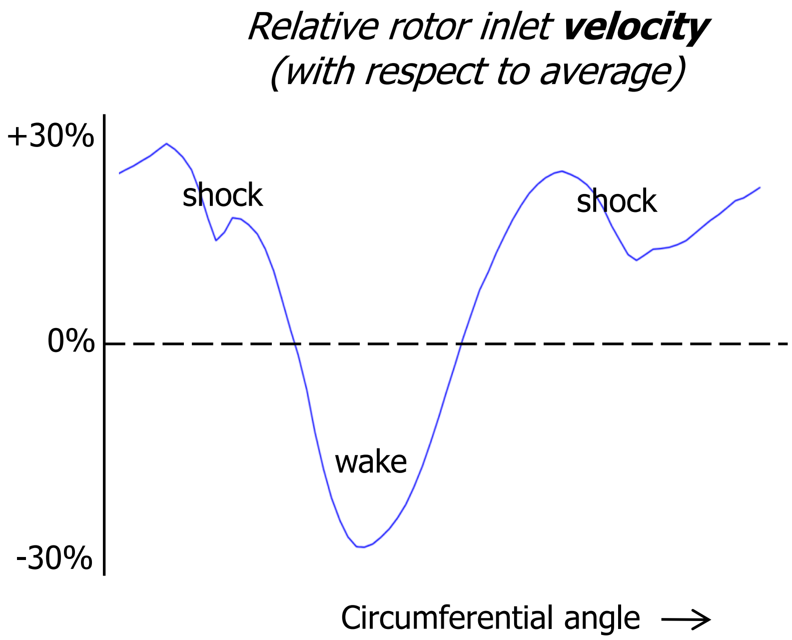




Results

Rotor inlet (midspan)





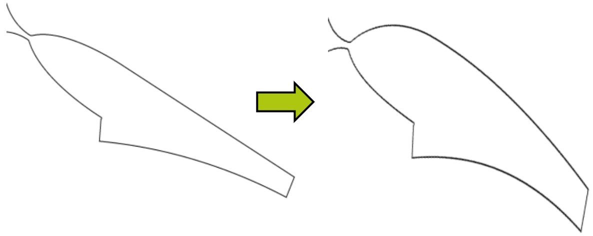
Options for further design improvement

Current design:

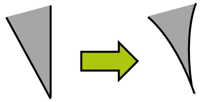
- Generally good turbine performance ($\eta_{is} \approx 70\%$)
- Arrangement of linear nozzles ⇨ flow impingement ⇨ shocks ⇨ nonuniform rotor inflow angle

Improvements to make it even better:

- Curving/bending stator nozzles



- Smaller stator trailing edge angle



- Geometry refinement using optimization methods coupled to CFD

Outlook

- Validation with experimental measurements
- Automatic shape optimization
- Unsteady flow analysis
- Uncertainty quantification
- Coupling multi-level analyses: cycle model + turbine CFD
- Virtual prototyping

Conclusions

- Demonstration of state of the art of ORC turbine fluid dynamic performance analysis
- Characteristics of ORC turbines:
  - expansion in dense-gas region, requiring accurate thermodynamic properties
  - Supersonic flow, shocks, effect on rotor inflow
- Options for further design improvement
- Outlook

Thank you