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\textsubscript{e} to 1 – 2 MW\textsubscript{e})
- low $T$ heat source (150 – 450\degree C)

**Example for heat source of $T=305$ \degree C:**

<table>
<thead>
<tr>
<th></th>
<th>Water</th>
<th>Toluene</th>
<th>MDM</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M$ [g/mol]</td>
<td>18</td>
<td>92</td>
<td>236</td>
</tr>
<tr>
<td>$\Delta h\text{turb}$ [kJ/kg K]</td>
<td>590</td>
<td>130</td>
<td>60</td>
</tr>
<tr>
<td>$\dot{V}_{\text{turb inlet}}$ [m$^3$/s]</td>
<td>0.01</td>
<td>0.03</td>
<td>0.06</td>
</tr>
</tbody>
</table>

**Organic fluids:**
Lower $\Delta h\text{turb}$ $\rightarrow$ fewer stages $\rightarrow$ **lower cost**

Lower rpm $\rightarrow$ **lower rpm**

Higher $\dot{V}$ $\rightarrow$ lower $D_{\text{spec}}$ $\rightarrow$ **higher efficiency**
Advantages of organic fluid for turbine

Optimal turbine for:

- low capacity (few kW\textsubscript{e} to 1 – 2 MW\textsubscript{e})
- low $T$ heat source (150 – 450°C)

- Select optimal fluid for given power level
- High efficiency turbine $\rightarrow$ high efficiency cycle (20% at 325°C TIT)
- Good part-load efficiency
- Dry expansion
- Simple configuration
- Lubricant
Flow analysis/design of ORC turbines

- Expansion in dense-gas region
  - Accurate thermophysical properties needed

- Low specific enthalpy drop ($\Delta h_{\text{turbine}}$)
  - High expansion ratio
  - Supersonic flow, compression shocks possible

Volumetric deviation from simple ideal gas law in $T$-$s$ diagram of an organic fluid
Differences due to (inaccurate) models

Example for a simulated expansion in an ORC stator:

<table>
<thead>
<tr>
<th></th>
<th>Flow solvers</th>
<th>Turbulence models</th>
<th>Accurate thermophysical models</th>
<th>Ideal gas law</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass flow</td>
<td>2%</td>
<td>1%</td>
<td>1%</td>
<td>15%</td>
</tr>
<tr>
<td>Efficiency</td>
<td>8%</td>
<td>2%</td>
<td>5%</td>
<td>n.a.</td>
</tr>
<tr>
<td>Outlet velocity</td>
<td>3%</td>
<td>1%</td>
<td>0%</td>
<td>50%</td>
</tr>
<tr>
<td>Outlet flow angle</td>
<td>2°</td>
<td>1°</td>
<td>0°</td>
<td>2°</td>
</tr>
<tr>
<td>Specific work</td>
<td>n.a.</td>
<td>n.a.</td>
<td>6%</td>
<td>n.a.</td>
</tr>
</tbody>
</table>
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:

<table>
<thead>
<tr>
<th>Simpler approach</th>
<th>Nowadays possible</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Inviscid flow solver</td>
<td>• Viscous turbulent solver</td>
</tr>
<tr>
<td>• Approximate thermodynamic model</td>
<td>• Highly accurate multiparameter equations of state</td>
</tr>
<tr>
<td>• 2D</td>
<td>• 3D</td>
</tr>
<tr>
<td>• Stator only</td>
<td>• Complete turbine</td>
</tr>
</tbody>
</table>
3D turbulent RANS simulation of ORC turbine

An example

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

Turbine:
- Single-stage radial low-reaction turbine
- High pressure ratio ($P_{\text{in}}/P_{\text{out}} > 100$),
- 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

<table>
<thead>
<tr>
<th></th>
<th>Method</th>
<th>Dimension</th>
<th>Component</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Euler</td>
<td>2D*</td>
<td>stator</td>
</tr>
<tr>
<td>2</td>
<td>Euler</td>
<td>3D</td>
<td>stator</td>
</tr>
<tr>
<td>3</td>
<td>Euler</td>
<td>Throughflow</td>
<td>stator-rotor</td>
</tr>
<tr>
<td>4</td>
<td>RANS</td>
<td>2D*</td>
<td>stator</td>
</tr>
<tr>
<td>5</td>
<td>RANS</td>
<td>3D</td>
<td>stator</td>
</tr>
<tr>
<td>6</td>
<td>RANS</td>
<td>3D</td>
<td>stator-rotor-diffuser</td>
</tr>
</tbody>
</table>

*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 $k - \omega$ 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

- wake
- shocks
- stator (Mach)
- rotor (pressure)
- Stator outlet (Mach)
Results

Rotor inlet (midspan)

Relative rotor inlet angle (with respect to average)

+10°

0°

-10°

Circumferential angle

Relative rotor inlet velocity (with respect to average)

+30%

0%

-30%

Circumferential angle

shock

wake

shock

shock

wake
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