Design of a Partial Admission Impulse Turbine for an Automotive ORC-Application

Harald S. Kunte, Joerg R. Seume

Outline

1. Motivation
2. Thermodynamic analysis
3. Design of the impulse turbine
4. Conclusion/Outlook
Objectives

Goals of automobile manufacturers:

• Reduction of fuel consumption
• Achieving emission targets
  → Increase efficiency of the power-train

Approach:
Energy recovery from the exhaust gas using an Organic Rankine Cycle (high percentage of exergy) (Span et al. 2011)
Thermodynamic model and limitations

### Thermodynamic analysis

**Model:**
- Investigation of the thermodynamic cycle for the design point
- Fluid properties: NIST Database 23 (Lemmon et al.)
- Parameter study (e.g. max. pressure, min. pressure)
- Supposed turbine efficiency: 70%

### Truck application; diesel-engine

<table>
<thead>
<tr>
<th></th>
<th>(m_{eg} [\text{kg/s}])</th>
<th>(T_{eg} [\text{K}])</th>
<th>(\Delta H_{T,eg;343K} [\text{kJ/s}])</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design point (DP)</td>
<td>0.249</td>
<td>615.15</td>
<td>78.5</td>
</tr>
<tr>
<td>Part-load (PL)</td>
<td>0.126</td>
<td>569.15</td>
<td>31.6</td>
</tr>
<tr>
<td>Overload (OL)</td>
<td>0.338</td>
<td>630.15</td>
<td>108.4</td>
</tr>
</tbody>
</table>

### Limitations of the ORC (predefined)

<table>
<thead>
<tr>
<th>Limitation</th>
<th>Criterion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max. pressure</td>
<td>40 bar</td>
</tr>
<tr>
<td>Min. pressure</td>
<td>0.5 bar</td>
</tr>
<tr>
<td>Min. (\Delta T) heat-exchangers</td>
<td>20 K</td>
</tr>
<tr>
<td>Min. (T) of condensation</td>
<td>343 K</td>
</tr>
</tbody>
</table>
Results of the thermodynamic analysis (DP)

- Ethanol promises highest power output
- Superheating decreases power output for ethanol

Kunte and Seume (2013)
Reason for negative effect of superheating (DP)

**Superheated fluid**

- ORC-Cycle
- Condensation line
- Exhaust gas temperature

**Fluid without superheating**

High efficiency of the stator causes an almost isentropic expansion in the nozzles:

- In Case of thermal equilibrium
  - → Risk of erosion due to droplets
  - → Temperature must be raised to avoid erosion
  - → Decreased power output

In reality:

Homogeneous nucleation effects delay droplet formation
Supersaturation of the vapour phase according to Hale (1988)

**Definition of saturation (WA (2005)):**

\[ S = \frac{p_{VAP}}{p_{VAP,s}(T)} \]

S=1: saturated
S>1: supersaturated

**Approach by Hale (1988):**

\[ \ln S = \left( \frac{36\pi}{\Omega} \right)^{1/2} x_0 \delta_0 \left( \frac{T_c}{T} - 1 \right)^{3/2} \]
Effect of supersaturation according to Hale (1988)

Benefits of supersaturation vs. equilibrium condensation ($n_T=0.7$):

<table>
<thead>
<tr>
<th></th>
<th>$\Delta P$ [%]</th>
<th>$\Delta P$ [W]</th>
<th>$P_{\text{Wilson}}$ [kW]</th>
<th>$\Pi$ [-]</th>
<th>$T_{\text{in}}$ [K]</th>
</tr>
</thead>
<tbody>
<tr>
<td>DP</td>
<td>+1.18</td>
<td>+118</td>
<td>10.20</td>
<td>49.1</td>
<td>522.2</td>
</tr>
<tr>
<td>PL</td>
<td>+0.62</td>
<td>+19</td>
<td>3.09</td>
<td>32.5</td>
<td>496.6</td>
</tr>
<tr>
<td>OL</td>
<td>+0.84</td>
<td>+127</td>
<td>15.13</td>
<td>39.2</td>
<td>508.0</td>
</tr>
</tbody>
</table>

Potential and uncertainties:

+ The expansion rate is no factor in this model.
  High expansion rates, like in laval-nozzles, promises considerably higher supersaturation (chosen model is very conservative) (Treffinger (1994))

+ The possible supersaturation for ethanol is higher than predicted by the model (vapour phase is stabilized by molecular associations) (WA (2005))

− Homogeneous nucleation requires very clean fluids (Bier et al. (1995))

− Uncertainties by the model itself (Treffinger (1994))
**Impulse turbine**

**Benefits of the axial impulse turbine:**
- High efficiency at high pressure ratios (Verneau (1987))
- Acceptable rotational speed (compared to other turbine designs)
- Single stage → compact
- Wide operating range due to variable partial admission

Stator:
Degree of reaction $R = \frac{\Delta h_{\text{static,Rotor}}}{\Delta h_{\text{static,stage}}} = 0$

The complete expansion takes place in the stator.

Rotor:
The rotor redirects the flow without a change of static pressure or the relative velocity ($|w_1| = |w_2|$)
Supersonic blade design

**Stator; Laval-nozzles:**
- Subsonic flow up to the throat \( \uparrow 1 \)
- Sonic velocity at the throat
- Supersonic flow in the divergent nozzle part \( \uparrow 2 \)

Flow direction

Kunte and Seume (2013)

**Rotor; Impulse blades:**
Sharp leading and trailing edges minimize supersonic shock losses

Kunte and Seume (2013)
Flow control

- Low mass flow:
- High mass flow:

Kunte and Seume (2013)

Outline

Motivation

Thermodynamic analysis

Design of the impulse turbine

Conclusion
Turbine design parameters and CFD

Preliminary design based on a model by Aungier (2006)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outer Diameter</td>
<td>65.2 mm</td>
</tr>
<tr>
<td>Rotational speed at DP</td>
<td>105,000 rpm</td>
</tr>
<tr>
<td>Partial Admission at DP(OL)</td>
<td>20 % (40 %)</td>
</tr>
</tbody>
</table>

CFD-Modell:
- Ansys CFX 13.0
- Steady-state calculation
- Frozen rotor interface
- 18 million cells (with full radial resolution)
- Q3D-calculations for the calculation of the operating curve (reduced radial resolution)
Performance prediction for the truck application

<table>
<thead>
<tr>
<th></th>
<th>DP</th>
<th>PL</th>
<th>OL</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\dot{m}$ [kg/s]</td>
<td>0.055</td>
<td>0.019</td>
<td>0.087</td>
</tr>
<tr>
<td>$p_{in}$ [bar]</td>
<td>39.8</td>
<td>26.3</td>
<td>31.8</td>
</tr>
<tr>
<td>$P_{aero}$ [kW]</td>
<td>8.5</td>
<td>1.9</td>
<td>14.1</td>
</tr>
<tr>
<td>$n_{is}$ [-]</td>
<td>0.58</td>
<td>0.44</td>
<td>0.65</td>
</tr>
</tbody>
</table>

DP: Design point
PL: Part-load
OL: Overload
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Design of the prototype

1. Turbine stator
2. Turbine rotor
3. Aerodynamically lubricated seals
4. Spindle ball bearing
5. Generator
6. Water cooling jacket
Conclusions

- Working fluid: Ethanol promises the highest power output for the considered application.
- An increase in power compared to thermal equilibrium is possible due to supersaturation in the preliminary performance prediction (Wilson line).
- The axial impulse turbine is suitable for the utilization as an expansion turbine for an automotive ORC (predicted efficiencies):
  - Design point: 58%
  - Part-load: 44%
  - Overload: 65%
- Coverage of the performance range requires variable partial admission
- Predicted rotational speeds allow direct coupling of turbine with the generator for compact design.

Outlook

- Detailed aerodynamic investigation with design improvement
- Prototyping for truck application
- Experimental verification
- Investigation of homogeneous nucleation with consideration of the expansion rate (e.g. Treffinger 1994) might further improve performance
Thank you for your attention!

Thanks to:
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