A turbine based domestic micro ORC system

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Introduction

• Nowadays, the world needs more responsible ways of energy conversion and use,
• Lots of households use solid fuel boilers for heating,
• A high quality fuel is used to rise the temperature only by a few degrees,
• The reason: cogeneration in the range up to 20 kW is technologically and economically challenging,
• MicroCHP technologies for solid fuels:
  • Stirling engines,
  • Peltier modules,
  • Steam systems,
  • **ORC systems,**
  • Other.
Solutions of ORC based systems

• Coupling an ORC to a typical domestic boiler, low temperature (90 °C) → poor efficiency,
• Pressurized water loop → high pressures,
• Thermal oil loop → relatively expensive,
• Direct evaporation → dangerous (potential explosions), risk of working fluid decomposition.
Domestic ORC system layout

**Indirect evaporation**

- Temperature [°C]
- Transferred heat rate [kW]

**Direct evaporation**

- Temperature [°C]
- Transferred heat rate [kW]

- Introducing a regenerator is an option
- Many fluids possible
- Expansion unit is a challenge
### Results examples for a 15 kW boiler

**Assumptions:**
- Expander efficiency (including electric generator): 55 %
- Pump efficiency: 40 %
- Evaporation temperature: 150 °C
- Cooling water temperature: 15 °C
- Warm water temperature: above 40 °C

<table>
<thead>
<tr>
<th>Fluid</th>
<th>Condensing</th>
<th>Turbine power [kW]</th>
<th>Pump power [kW]</th>
<th>Net efficiency [%]</th>
<th>mass flow [kg/s]</th>
<th>(p_{ev}) [bar(a)]</th>
<th>(p_{cond}) [bar(a)]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cyclopentane</td>
<td>Above atmospheric pressure</td>
<td>1.46</td>
<td>0.1</td>
<td>9.7</td>
<td>0.029</td>
<td>10.67</td>
<td>1.04</td>
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<tr>
<td>Acetone</td>
<td></td>
<td>1.32</td>
<td>0.07</td>
<td>8.8</td>
<td>0.023</td>
<td>10.34</td>
<td>1.01</td>
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<tr>
<td>HFE7100</td>
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<td>1.19</td>
<td>0.12</td>
<td>7.9</td>
<td>0.1</td>
<td>8.21</td>
<td>1.02</td>
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<tr>
<td>Cyclohexane</td>
<td>Below atmospheric pressure</td>
<td>1.54</td>
<td>0.05</td>
<td>10.3</td>
<td>0.03</td>
<td>5.00</td>
<td>0.36</td>
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<tr>
<td>MM</td>
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<td>1.47</td>
<td>0.05</td>
<td>9.5</td>
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<td>0.21</td>
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<td>1.40</td>
<td>0.12</td>
<td>9.4</td>
<td>0.095</td>
<td>8.21</td>
<td>0.66</td>
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</table>
Most important turbine design features

<table>
<thead>
<tr>
<th>Fluid</th>
<th>$N_s$ 30 krpm</th>
<th>$N_s$ 60 krpm</th>
<th>$N_s$ 100 krpm</th>
<th>$N_s$ 150 krpm</th>
<th>$N_s$ 200 krpm</th>
<th>$n_{opt}$ [krpm]</th>
<th>$u_{impulse}$ [m/s]</th>
<th>$u_{reaction}$ [m/s]</th>
<th>$A_{1x}$ [mm²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cyclopentane</td>
<td>0.010</td>
<td>0.019</td>
<td>0.032</td>
<td>0.048</td>
<td>0.064</td>
<td>280</td>
<td>203</td>
<td>287</td>
<td>8.9</td>
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<tr>
<td>Acetone</td>
<td>0.008</td>
<td>0.017</td>
<td>0.028</td>
<td>0.042</td>
<td>0.055</td>
<td>325</td>
<td>216</td>
<td>305</td>
<td>7.9</td>
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<tr>
<td>HFE7100</td>
<td>0.029</td>
<td>0.057</td>
<td>0.095</td>
<td>0.143</td>
<td>0.190</td>
<td>94</td>
<td>101</td>
<td>142</td>
<td>19.6</td>
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<tr>
<td>Cyclohexane</td>
<td>0.016</td>
<td>0.031</td>
<td>0.052</td>
<td>0.078</td>
<td>0.104</td>
<td>174</td>
<td>203</td>
<td>286</td>
<td>18.2</td>
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<tr>
<td>MM</td>
<td>0.031</td>
<td>0.061</td>
<td>0.102</td>
<td>0.154</td>
<td>0.205</td>
<td>88</td>
<td>150</td>
<td>213</td>
<td>33.9</td>
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<tr>
<td>HFE7100</td>
<td>0.030</td>
<td>0.059</td>
<td>0.099</td>
<td>0.149</td>
<td>0.198</td>
<td>91</td>
<td>111</td>
<td>157</td>
<td>18.7</td>
</tr>
</tbody>
</table>

Where:

- $N_s$ – specific speed
- $n_{opt}$ – approximate optimal rotational speed
- $u_{impulse}$ – rotor peripheral speed in a single stage impulse turbine
- $u_{reaction}$ – rotor peripheral speed in a single stage reaction turbine
- $A_{1x}$ – total area of nozzle critical section
Single stage impulse turbines

**Advantages:**

- Simple design,
- Low axial thrust,
- Can be relatively efficient even at low specific speeds (partial admission possible).

**Disadvantages:**

- Worse efficiency than reaction stages,
- Worse off-design performance than multistage designs,
Impulse turbines performance and features (correlation based)
Examples for 100 krpm limit (high condensing pressure)

Cyclopentane
η = 67%
n = 100 krpm
ε = 33%

Acetone
η = 65%
n = 100 krpm
ε = 29%

HFE7100
η = 78.2%
n = 75 krpm
ε = 100%
Examples for 100 krpm limit (low condensing pressure)

Cyclohexane
\[ \eta = 74.4\% \]
\[ n = 100 \text{ krpm} \]
\[ \varepsilon = 61\% \]

MM
\[ \eta = 80.1\% \]
\[ n = 72 \text{ krpm} \]
\[ \varepsilon = 100\% \]

HFE7100
\[ \eta = 78.6\% \]
\[ n = 73 \text{ krpm} \]
\[ \varepsilon = 100\% \]
Case study – acetone turbine off-design performance (constant back pressure)
Case study – acetone turbine blade geometry and CFD
Case study – 3 kW HFE7100 turbine influence of tip clearance on optimal admission
Reaction (radial inflow) turbine example

Acetone
\( \eta = 84.2\% \)
\( n = 243 \) krpm
Conclusions

• It is feasible to design turbines for very small power that achieve acceptable efficiencies,
• Single stage impulse turbines are a simple and attractive option,
• Reaction turbines are more efficient but more difficult to build,
• The sizes, efficiencies, peripheral speeds and rotational speeds vary strongly with respect to different working fluids.
Acknowledgements

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