Efficiency Correlations for Off-Design Performance Prediction of ORC Axial-Flow Turbines

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Outline

1. Axial-Flow Turbines for ORC Power Systems
2. Design and Optimization of Axial-Flow Turbines
3. Turbine Design Tool: AxialOpt
4. Turbine Off-design Tool: AxialOff
5. Test cases
6. Results and Correlations
7. Summary and Future Outlook
1. Axial-Flow Turbines for ORC Power Systems

Expander:
- Thermo-mechanical conversion
- Crucial component for high efficiency

Classical design of ORC power systems:
→ Assumed constant, reasonable isentropic efficiency of turbine

Integrated ORC/expander design:
→ Both ORC and expander design in the same optimization loop or
→ Expander design characterized by correlations

Off-design prediction
→ Model-based or correlations
1. Axial-Flow Turbines for ORC Power Systems

Axial-flow turbines are the dominant type of expander for large-scale ORC units.
→ Efficient in broad range of application
→ Advantageous for high specific speed (increased number of stage)
2. Design of Axial-Flow Turbines

Integral ORC/turbine design:
→ mean-line models based on flow deviation and loss correlations
→ codes available:
  1) Axtur (Macchi and Perdichizzi, 1981)
  2) Turax (Meroni et al, 2016a)
  3) AxialOpt (Agromayor and Nord, 2019)

To reduce computational effort:
→ efficiency correlations developed by Astolfi and Macchi (2015) for one, two and three-stage turbines

Function of:
\[ SP = \frac{\dot{V}_{out, is}}{\Delta h_{is}^{0.25}} \]
\[ V_r = \frac{\dot{V}_{out, is}}{\dot{V}_{in}} \quad + \text{for optimal specific speed} \]

1) Objective function:
\[
\eta = \frac{h_{0,\text{in}} - h_{\text{out}}}{h_{0,\text{in}} - h_{\text{out},s} - \phi_E - \frac{v_{\text{out,a}}^2}{2}}
\]

2) Fixed input parameters:
   - working fluid
   - mass flow rate
   - stagnation temperature and pressure at inlet
   - static pressure at outlet

3) Constraints

4) Craig and Cox method, 1970

5) Optimization in MATLAB® with fmincon (SQP algorithm) and MultiStart

Figure 5: Axial-radial view of stator and rotor blades (Agromayor, 2019).
3. AxialOpt – Validation

Comparison with Axtur (Astolfi and Macchi, 2015)

<table>
<thead>
<tr>
<th>Working fluid →</th>
<th>R125</th>
<th>Hexane</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Axtur</td>
<td>AxialOpt</td>
</tr>
<tr>
<td>Inlet stag. temperature, °C</td>
<td>155.0</td>
<td>155.0</td>
</tr>
<tr>
<td>Inlet stag. pressure, bar</td>
<td>36.200</td>
<td>36.200</td>
</tr>
<tr>
<td>Outlet static pressure, kPa</td>
<td>15.685</td>
<td>15.685</td>
</tr>
<tr>
<td>Mass flow rate, kg/s</td>
<td>11.89</td>
<td>11.89</td>
</tr>
<tr>
<td>Volumetric ratio, -</td>
<td>2.293</td>
<td>2.312</td>
</tr>
<tr>
<td>Size parameter, m</td>
<td>0.036</td>
<td>0.036</td>
</tr>
<tr>
<td>Rotational speed, rpm</td>
<td>31 000</td>
<td>29 660</td>
</tr>
<tr>
<td>Mean diameter, m</td>
<td>0.086</td>
<td>0.086</td>
</tr>
<tr>
<td>Isentropic efficiency, %</td>
<td>87.2</td>
<td>87.1</td>
</tr>
</tbody>
</table>
4. AxialOff – Part-load Behaviour

1) Based on AxialOpt

2) Input parameters:
   - working fluid
   - stagnation temperature and pressure at inlet
   - static pressure at outlet
   - rotational speed

3) Geometry fixed

4) Constraint: mass flow rate <= critical mass flow rate (choking)

5) Solution in MATLAB® with fmincon (target zero, SQP algorithm)

Figure 6: Axial view of stator and rotor blades (Agromayor, 2019).
4. AxialOff – Validation

Figure 7: Validation against experimental data (single-stage) from Kofskey and Nusbaum (1972).
4. AxialOff – Validation

Figure 8: Validation against experimental data (two-stages) from Kofskey and Nusbaum (1972).
5. Test cases

<table>
<thead>
<tr>
<th>No.</th>
<th>Application</th>
<th>Working fluid</th>
<th>Stagnation inlet temperature, °C</th>
<th>Stagnation inlet pressure, bar</th>
<th>Static outlet pressure, bar</th>
<th>Mass flow rate, kg/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Biomass</td>
<td>MDM</td>
<td>305.00</td>
<td>7.92</td>
<td>0.22</td>
<td>5.46</td>
</tr>
<tr>
<td>2</td>
<td>Biomass</td>
<td>Toluene</td>
<td>292.02</td>
<td>21.90</td>
<td>0.41</td>
<td>13.69</td>
</tr>
<tr>
<td>3</td>
<td>Geothermal</td>
<td>R1234yf</td>
<td>128.50</td>
<td>42.57</td>
<td>8.44</td>
<td>190.73</td>
</tr>
<tr>
<td>4</td>
<td>WHR Cement</td>
<td>Pentane</td>
<td>162.00</td>
<td>19.40</td>
<td>1.03</td>
<td>16.67</td>
</tr>
<tr>
<td>5</td>
<td>WHR Ship</td>
<td>Benzene</td>
<td>225.34</td>
<td>19.66</td>
<td>0.16</td>
<td>3.06</td>
</tr>
<tr>
<td>6</td>
<td>WHR Steel</td>
<td>Toluene</td>
<td>290.85</td>
<td>5.21</td>
<td>0.15</td>
<td>11.74</td>
</tr>
<tr>
<td>7</td>
<td>n/a</td>
<td>R125</td>
<td>155.00</td>
<td>36.20</td>
<td>15.69</td>
<td>11.89</td>
</tr>
<tr>
<td>8</td>
<td>n/a</td>
<td>Hexane</td>
<td>155.10</td>
<td>8.29</td>
<td>0.25</td>
<td>2.04</td>
</tr>
</tbody>
</table>

Pressure ratios: 2-124
Isentropic power output: 250 kW-2.5 MW
Molecular mass: 72-237 kg/kmol
## 6. Results - Turbine Design

<table>
<thead>
<tr>
<th>No.</th>
<th>Working fluid</th>
<th>Isentr. volume ratio, -</th>
<th>Isentr. size parameter, m</th>
<th>Isentropic efficiency, %</th>
<th>AxialOpt</th>
<th>Axtur (diff, %)</th>
<th>AxialOff (diff, %)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>1</td>
<td>MDM</td>
<td>41.91</td>
<td>0.13</td>
<td></td>
<td>82.3</td>
<td>85.6</td>
<td>86.9</td>
</tr>
<tr>
<td>2</td>
<td>Toluene</td>
<td>58.74</td>
<td>0.18</td>
<td></td>
<td>84.7</td>
<td>86.3</td>
<td>87.5</td>
</tr>
<tr>
<td>3</td>
<td>R1234yf</td>
<td>6.14</td>
<td>0.16</td>
<td></td>
<td>88.4</td>
<td>78.4</td>
<td>79.1</td>
</tr>
<tr>
<td>4</td>
<td>Pentane</td>
<td>23.17</td>
<td>0.14</td>
<td></td>
<td>82.4</td>
<td>87.1</td>
<td>88.7</td>
</tr>
<tr>
<td>5</td>
<td>Benzene</td>
<td>112.15</td>
<td>0.12</td>
<td></td>
<td>76.3</td>
<td>87.7</td>
<td>88.3</td>
</tr>
<tr>
<td>6</td>
<td>Toluene</td>
<td>31.82</td>
<td>0.29</td>
<td></td>
<td>82.7</td>
<td>85.5</td>
<td>86.6</td>
</tr>
<tr>
<td>7</td>
<td>R125</td>
<td>2.29</td>
<td>0.04</td>
<td></td>
<td>87.1</td>
<td>87.7</td>
<td>88.3</td>
</tr>
<tr>
<td>8</td>
<td>Hexane</td>
<td>34.35</td>
<td>0.09</td>
<td></td>
<td>81.5</td>
<td>85.0</td>
<td>86.0</td>
</tr>
</tbody>
</table>

### Pressure ratios:
2-124

### Isentropic power output:
250 kW-2.5 MW

### Molecular mass:
72-237 kg/kmol
6. Results - Part-load Correlations

Geometry designed with AxialOpt and part-load simulated with AxialOff

| Coefficients | Number of stages, -
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td>$a$</td>
<td>0.245</td>
</tr>
<tr>
<td>$b$</td>
<td>1.632</td>
</tr>
<tr>
<td>$c$</td>
<td>-1.940</td>
</tr>
<tr>
<td>$d$</td>
<td>0.033</td>
</tr>
<tr>
<td>$e$</td>
<td>-1.085</td>
</tr>
<tr>
<td>$f$</td>
<td>2.112</td>
</tr>
<tr>
<td>$R^2$</td>
<td>0.994</td>
</tr>
</tbody>
</table>

\[
\frac{\eta}{\eta_D} = a + b \left( \frac{\Delta h}{\Delta h_D} \right) + c \left( \frac{\Delta h}{\Delta h_D} \right)^2 + d \left( \frac{\dot{V}_{out}}{\dot{V}_{out_D}} \right) + e \left( \frac{\dot{V}_{out}}{\dot{V}_{out_D}} \right)^2 + f \left( \frac{\Delta h}{\Delta h_D} \right) \left( \frac{\dot{V}_{out}}{\dot{V}_{out_D}} \right)
\]
6. Results - Comparison

Comparison with turbine out of pool for correlation development

Turbine (Meroni, 2016)
Working fluid R245fa
Pressure ratio: 2.83
Size parameter: 0.082 m

<table>
<thead>
<tr>
<th>Turbine stages</th>
<th>Coefficient of determination, $R^2$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>96.6</td>
</tr>
<tr>
<td>2</td>
<td>90.0</td>
</tr>
<tr>
<td>3</td>
<td>94.9</td>
</tr>
</tbody>
</table>

Figure 9: Validation against additional turbine from Meroni (2016b).
7. Summary and Future Outlook

Summary
Two tools for design optimization (AxialOpt) and part-load prediction (AxialOff) of ORC axial-flow turbines based on mean-line method are presented.

The tools have been applied to design and study the part-load of turbines from several applications (broad range).

Correlations for the performance prediction of axial-flow turbines in part-load have been developed.

Future outlook
Further comparison with operational data.
References


Thank you very much for the attention.

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