Thermodynamic potential of Rankine and flash cycles for waste heat recovery in a heavy duty Diesel engine

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Purpose of this study

- Thermodynamic potential of WHR for low- and high-temperature heat sources in a heavy duty Diesel engine

- Identify heat sources inside the engine

- Simulations to evaluate the performance of various thermodynamic cycles using different working fluids
Heat sources

Volvo D13 EGR engine

Four available heat sources:
- Charge air cooler (CAC)
- Coolant
- Exhaust gas recirculation cooler (EGRC)
- Exhaust gas out

Energy and exergy analysis
Heat sources – Methods

- GT-Power model
- Validated with experiments in previous project
- Twelve operating points of European Stationary Cycle (ESC)
Heat sources – Results

Analysis based on heat and exergy losses for the ESC operating points

Exergy loss:

\[ \dot{X}_{loss} = \dot{Q}_{loss} \frac{T - T_0}{T} \]

All heat sources show potential for waste heat recovery
Heat sources – Results

Selected operating point for cycle simulations: ESC A50

<table>
<thead>
<tr>
<th>Source</th>
<th>Fluid</th>
<th>$P$ [bar]</th>
<th>$\dot{m}$ [g/s]</th>
<th>$T_{\text{in}}$ [°C]</th>
<th>$T_{\text{out}}$ [°C]</th>
</tr>
</thead>
<tbody>
<tr>
<td>CAC</td>
<td>Air</td>
<td>2.5</td>
<td>231</td>
<td>152</td>
<td>60</td>
</tr>
<tr>
<td>Coolant</td>
<td>Water</td>
<td>1.013</td>
<td>4317</td>
<td>93</td>
<td>90</td>
</tr>
<tr>
<td>EGRC</td>
<td>Exhaust gas</td>
<td>2.5</td>
<td>73</td>
<td>472</td>
<td>95</td>
</tr>
<tr>
<td>Exhaust</td>
<td>Exhaust gas</td>
<td>1.013</td>
<td>239</td>
<td>251</td>
<td>100</td>
</tr>
</tbody>
</table>
Cycles

- Rankine cycle (RC)
- Transcritical Rankine cycle (TRC)
- Trilateral flash cycle (TFC)
Cycles

• Single flash cycle (SFC)
# Working fluids

<table>
<thead>
<tr>
<th>Fluid</th>
<th>$T_{cr}$ [°C]</th>
<th>$P_{cr}$ [bar]</th>
<th>$T_{1atm}$ [°C]</th>
<th>$P_{40C}$ [bar]</th>
<th>Type</th>
<th>GWP$_{100}$</th>
<th>ODP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cyclopentane</td>
<td>239</td>
<td>46</td>
<td>0.7</td>
<td>49</td>
<td>Isen.</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Ethanol</td>
<td>240</td>
<td>63</td>
<td>0.2</td>
<td>78</td>
<td>Wet</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>R245fa</td>
<td>154</td>
<td>37</td>
<td>2.5</td>
<td>15</td>
<td>Dry</td>
<td>858</td>
<td>0</td>
</tr>
<tr>
<td>Water</td>
<td>374</td>
<td>220</td>
<td>0.1</td>
<td>100</td>
<td>Wet</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
Conditions and constraints

- Fixed heat input (constant source temperature profile)

- Potential:
  - Low condensation temperature
  - No limitation on condensation pressure
  - High efficiencies
# Conditions and constraints

## Reference and boundary conditions

<table>
<thead>
<tr>
<th>Condition</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ambient temperature</td>
<td>25 °C</td>
</tr>
<tr>
<td>Ambient pressure</td>
<td>1.013 bar</td>
</tr>
<tr>
<td><strong>Condensation temperature</strong></td>
<td>40 °C</td>
</tr>
<tr>
<td>Pump isentropic efficiency</td>
<td>0.80</td>
</tr>
<tr>
<td><strong>Expander isentropic efficiency</strong></td>
<td>0.85*</td>
</tr>
<tr>
<td>Pump vapour quality in</td>
<td>0</td>
</tr>
</tbody>
</table>

## Constraints

<table>
<thead>
<tr>
<th>Constraint</th>
<th>Max.</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>High pressure</td>
<td></td>
<td>100 bar</td>
</tr>
<tr>
<td><strong>Superheating evaporation</strong></td>
<td></td>
<td>20 K</td>
</tr>
<tr>
<td><strong>Superheating condensation</strong></td>
<td></td>
<td>20 K</td>
</tr>
<tr>
<td>Pinch point difference</td>
<td>Min.</td>
<td>10 K</td>
</tr>
<tr>
<td>Expander vapor quality out</td>
<td>Min.</td>
<td>0.85</td>
</tr>
</tbody>
</table>

*: RC, TFC, SFC

**: TFC
Four heat sources

Dymola / Modelica
CoolProp
Python

Simulations

Four cycles

Four working fluids

Conditions and constraints

Reference and boundary conditions:
- Ambient temperature: 25 °C
- Ambient pressure: 1.013 bar
- Condensation temperature: 40 °C
- Pump isentropic efficiency: 0.80
- Expander isentropic efficiency: 0.80
- Pump vapour quality in: 0

Constraints:
- High pressure: Max. 1000 bar
- Superheating evaporation: Max. 25 °C
- Superheating condensation: Max. 25 °C
- Flash point differences: Min. 15 K
- Expander vapor quality out: Min. 0.65
Results – Thermal efficiencies
Results – Net power

[CAC, Coolant, EGRC, Exhaust graphs with data for different molecules and components]
Conclusions

• All four available heat sources inside the engine show potential for waste heat recovery

• Best performing cycles and working fluids depend on heat source:
  • CAC:  SFC, TFC  - All fluids  →  2 kW power
  • Coolant:  RC  - All fluids  →  5 kW power
  • EGRC:  RC, TRC  - Ethanol  →  8 kW power
  • Exhaust:  All cycles  - All fluids  →  6 kW power

• Choice of cycle showed largest impact on performance
  • Thermal matching and cycle constraints
Acknowledgements