Rankine system design for commercial vehicle application with GT-SUITE
Agenda

1. Context
2. Vehicle level analysis
3. System level analysis
4. Conclusions
Introduction
Energy balance on a truck

FUEL 100%

To Crankshaft 43%
To Cooling: 23%
To Exhaust 34%
To Wheels 40%
EATS out 23%

Rejected to air 23%

Drivetrain losses 1.5%
Auxiliaries 1.5%

Turbo charger 8%
Thermal losses 3%

About 60% of fuel energy rejected as thermal energy!
Introduction

Rankine basic layout

Heat source: Exhaust gases

Electric or mechanic

Heat sink: Engine coolant or ambient air

Rankine main benefit is the low pumping work compared to expansion work

\[ \eta_{th} = \frac{\dot{W}_{exp} - \dot{W}_{pump}}{Q_{in}} \]
Introduction
System engineering method and tools

1. Analyze Exhaust and cooling flux
   • Mission profile analysis on a reference trip
   • Define operating condition

2. Internal functional analysis
   • Define proper design variables and constraints
   • Study different architectures (heat sink / fluid / heat source)
   • Build component specifications

3. Optimisation of \( \frac{\text{system cost}}{\text{Power output}} \) ratio
   • Select best component technologies
   • Optimize design parameters to lower system cost
   • Validate system performances

GT-Suite is completely integrated in our system engineering process
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**Vehicle analysis**

**Vehicle configuration**

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**Typical long haul truck configuration – Full load (40T)**

<table>
<thead>
<tr>
<th>Engine: DAF Paccar Mx375</th>
<th>Truck</th>
<th>Tractor</th>
<th>Trailer + Cargo</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Displacement</strong></td>
<td>7000</td>
<td>33000</td>
<td></td>
</tr>
<tr>
<td><strong>Max Power</strong></td>
<td>375 kW @ 1500-1900 rpm</td>
<td>3.3</td>
<td>0.5</td>
</tr>
<tr>
<td><strong>Max Torque</strong></td>
<td>2500 Nm @ 1000-1500 rpm</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>EGR</strong></td>
<td>No</td>
<td></td>
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</tr>
</tbody>
</table>

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**Engine Torque / Power**

![Engine Torque / Power graph]

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**Engine Specifications**

- **Engine:** DAF Paccar Mx375
- **Displacement:** 6 Cylinders 12.9 L
- **Max Power:** 375 kW @ 1500-1900 rpm
- **Max Torque:** 2500 Nm @ 1000-1500 rpm
- **EGR:** No
Objective: generate exhaust and cooling boundaries conditions
Mission profile analysis main objective is to answer the following questions:

- What is recovery potential on my journey => exhaust temperature and energy
- What is cooling potential of my cold source => Cooling temperature and max cooling capacity

**Vehicle analysis**

**Interface analysis**

**Rankine operating conditions bounded by exhaust energy and cooling capacity**
Vehicle analysis
Complete vehicle model

Cooling circuit
• Radiator performances
• Coolant flow

Engine
• BSFC
• Exhaust temperature
• Exhaust flow
• Cooling heat rejection

Exhaust System
• Thermal inertia
• Thermal losses

Engine characterized on test bench to build full vehicle model

CVE test cell
External functional analysis

Exhaust layout

- Exhaust boiler always located downstream Exhaust Aftreatment System (EATS)
  - Temperature mandatory for DOC / SCR conversion efficiency
- EGR not always present on OEM architecture
  - Economical interest: EGR rates / exchanger cost
  - Main issue: guaranty at any time EGR cooling function

No EGR available on our engine: “without EGR” case studied
# External functional analysis

## Cooling circuit architecture

<table>
<thead>
<tr>
<th>Engine coolant</th>
<th>Engine coolant</th>
<th>Engine coolant</th>
<th>Air Direct Air cooling</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Serial</strong></td>
<td><strong>Parallel</strong></td>
<td><strong>Dedicated loop</strong></td>
<td></td>
</tr>
<tr>
<td>$T_{\text{cool}} = 80^\circ\text{C}$</td>
<td>$T_{\text{cool}} = 60^\circ\text{C}$</td>
<td>$T_{\text{cool}} = 40^\circ\text{C}$</td>
<td>$T_{\text{cool}} = 25^\circ\text{C}$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th>Air flow</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>CAC</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>RADIATOR</td>
</tr>
</tbody>
</table>

- Condenser upstream water pump
- Condenser parallel to radiator
- Condenser in auxiliary cooling loop
- Condenser upstream front end radiator

- Easy integration
- Higher cooling potential
- Do not impact engine
- Lowest cooling temperature

- Increase main circuit pressure drop
- Require additional pump
- Architecture not yet available
- Increase radiator inlet temperature CaC outlet temperature at high load

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**The lower the cold source temperature, the lower the condensing pressure**
Exhaust energy distribution vs exhaust power is the key criteria to select nominal point
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Simulation will help us to define component ideal architecture and specifications.
Simulation helps us to understand physics and define realistic boiler specifications.
## System level analysis

### Expander selection

<table>
<thead>
<tr>
<th></th>
<th><strong>Scroll</strong></th>
<th><strong>Piston</strong></th>
<th><strong>Turbine</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Machine type</strong></td>
<td>Volumetric / Continuous flow</td>
<td>Volumetric / Alternative flow</td>
<td>Dynamic / Continuous flow</td>
</tr>
<tr>
<td><strong>Pressure ratio range</strong></td>
<td>Up to 7</td>
<td>&gt; 20 (design dependent)</td>
<td>Up to 10</td>
</tr>
<tr>
<td><strong>Efficiencies range</strong></td>
<td>50% – 70%</td>
<td>50% - 70%</td>
<td>70%-80%</td>
</tr>
<tr>
<td><strong>Pro</strong></td>
<td>Liquid phase proof Low speed (engine coupling)</td>
<td>Liquid phase proof (limited) Low speed (engine coupling)</td>
<td>No lubrication in fluid compact</td>
</tr>
<tr>
<td><strong>Cons</strong></td>
<td><strong>Lubrication</strong> Friction</td>
<td><strong>Lubrication</strong> compression work Friction</td>
<td>Need dry fluid or complex control High speed (complex coupling)</td>
</tr>
<tr>
<td><strong>Intrinsic limitations</strong></td>
<td>Low efficiency at high pressure ratio (leakages)</td>
<td>Low efficiency at low pressure ratio</td>
<td>Rotor specific speed / nozzle outlet Mach number</td>
</tr>
<tr>
<td><strong>Modelling technique</strong></td>
<td></td>
<td>Volumetric efficiency and Isentropic efficiency map</td>
<td>Calibrated Nozzle and isentropic efficiency map</td>
</tr>
</tbody>
</table>

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**Expander matching is a key design criteria for system design**
# System Internal Architecture

## Architecture study

- **Alcohols favorable to each cooling architecture**
  - Piston seems to be favorable because of high pressure ratio
  - Fluid 1 could be a good alternative because it has better performances at low temperature. Expander selection opened

- **Organic fluid only interesting with direct air cooling (low temp cold source)**
  - Scroll or single stage turbine are well adapted (compactness)
  - Fluid 2 increase a little bit performances but still interesting only for direct cooling
  - Performances of these fluids can be increased with a regenerator

<table>
<thead>
<tr>
<th>Fluid</th>
<th>Cooling architecture</th>
<th>Fuel saving %</th>
<th>Expander rating</th>
<th>Fluid properties</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>pessimistic</td>
<td>optimistic</td>
<td>Flexibility</td>
</tr>
<tr>
<td>Ethanol</td>
<td>direct</td>
<td>4.24</td>
<td>5.69</td>
<td>15.92</td>
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<tr>
<td>Ethanol</td>
<td>parallel</td>
<td>4.24</td>
<td>6.09</td>
<td>15.92</td>
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<td>Ethanol</td>
<td>serial</td>
<td>3.63</td>
<td>5.23</td>
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<tr>
<td>Cyclopentane</td>
<td>direct</td>
<td>5.40</td>
<td>7.86</td>
<td>15.92</td>
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<td>Cyclopentane</td>
<td>parallel</td>
<td>4.17</td>
<td>6.13</td>
<td>10.45</td>
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<td>Cyclopentane</td>
<td>serial</td>
<td>3.14</td>
<td>4.68</td>
<td>6.12</td>
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<tr>
<td>R245fa</td>
<td>direct</td>
<td>3.28</td>
<td>4.94</td>
<td>5.99</td>
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<tr>
<td>R245fa</td>
<td>parallel</td>
<td>2.15</td>
<td>3.33</td>
<td>3.28</td>
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<tr>
<td>R245fa</td>
<td>serial</td>
<td>1.21</td>
<td>1.95</td>
<td>1.99</td>
</tr>
<tr>
<td>DR2</td>
<td>direct</td>
<td>3.66</td>
<td>5.50</td>
<td>13.54</td>
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<tr>
<td>DR2</td>
<td>parallel</td>
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<td>3.90</td>
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<td>1.72</td>
<td>2.78</td>
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<td>Agenda</td>
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<td></td>
</tr>
<tr>
<td>1</td>
<td>Context</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Vehicle level analysis</td>
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<td></td>
</tr>
<tr>
<td>3</td>
<td>System level analysis</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Conclusions</td>
<td></td>
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</tbody>
</table>
This methodology has been applied to build a demo truck with industrial partners.

More information at 12th international MTZ Conference on Heavy Duty Engines, Augsburg 28/11 – 29/11 2017

- Rankine cycle, from thermodynamic equations to road test (ATZ 2017)

**Faurecia EHPG DemoTruck**

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Truck type</strong></td>
<td>Renault Truck T460</td>
</tr>
<tr>
<td><strong>Engine</strong></td>
<td>DTI 11L</td>
</tr>
<tr>
<td><strong>Working Fluid</strong></td>
<td>Ethanol</td>
</tr>
<tr>
<td><strong>Expander</strong></td>
<td>Exoes EVE (swashplate Piston)</td>
</tr>
</tbody>
</table>
Summary

- FCM develops engineering method & tools to study and size Rankine system for a long haul truck
  - Full system model
  - Test beds
  - Vehicle measurements

- Mission profile analysis to identify exhaust / cooling / mechanical boundaries
  - Proof of concept
  - Component specifications

- GT-Suite completely integrated in our model-based design process
  - Support control software development
  - Dynamic modelling to reproduce road test and improve system