Organic Rankine Cycles (ORC)

Introduction

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Ph.D. Student
Contents

- Introduction
- Working Principles
- Efficiency Comparison
- Applications
- Conclusions
Introduction

Who?

- **William John Macquorn Rankine** (1820 – 1872)
  - Scottish physicist and engineer
  - One of the «fathers» of Thermodynamics
  - Important contributions to the theory of the steam engine
    - Theory of the *Rankine Cycle (RC)*
Introduction

First Applications – Rankine Cycle (RC)

- Steam Locomotives
- Steam Ships (*Titanic*)
- Use of water-steam as working fluid

*Oliver Dingel, EORCC 2016, Belfast*
**Introduction**

First Applications – RMS Titanic Engine + WHR

- **RMS Titanic**

  ![Schematic of Titanic's Propulsion Plant](http://www.titanicology.com)

  **Boilers:**
  - **N° 29**
  - **D = 4.80 m**
  - **L = 6.1 m**

  **Reciprocating engine:**
  - **Inverted Double-Acting, Triple expansion**
  - **N° 2**
  - **N° cyl 4**
  - **H = 9.14 m**
  - **HP cyl Bore = 1.37 m**
  - **IP cyl Bore = 2.13 m**
  - **LP cyl Bore = 2.46 m**
  - **Stroke = 1.90 m**
  - **Weight = 1.000 t/engine**

  **LP Turbine:**
  - **Direct coupled, multistage reaction type Parsons turbine**
  - **N° 1**
  - **D = 3.66 m**
  - **L = 3.86 m**

*Oliver Dingel, EORCC 2016, Belfast*
Introduction
Steam Turbine Power Plants and Combined Cycles

- Actual main example of Rankine Cycle use
- Coal or Natural Gas fired plants

Introduction
Why and when to consider ORC?

- Low grade heat (100 – 150°C) released into the environment contributes to «heat pollution» and is a loss.
- Steam Rankine Cycle more effective above 300 - 350°C.
- Need to recover low temperature heat sources in an efficient way.
- Use of low boiling temperature and critical temperature fluids.

![Graph showing different ORC applications versus temperature and output power.](Image)
**Introduction**

**RC vs ORC**

- **High enthalpy drop**
- **High level of superheating needed**
- **Risk of blade erosion (pitting) – «wet fluid»**
- **Water treatment required**
- **Highly skilled personnel required**
- **High pressures and temperatures involved**
- **Convenient for large power plants (>10MW)**
- **Low flexibility**
- **Low performance at part load**

- **Small enthalpy drop (reduced expansion machines complexity)**
- **No need of high degree of superheat (limited dimensions)**
- **No risk of blade erosion (dry or isentropic fluids)**
- **Minimum personnel requirements**
- **Completely automatic systems available**
- **High flexibility and good performance at part load**
- **Well proven technology in industrial heat recovery and stationary applications**

*Turbođen, Foresti, Kiev, 2015*
Contents

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Reversible cycle

Highest possible efficiency of any closed power cycle between 2 fixed temperatures

It is impractical to be developed

\[ \eta_{\text{Carnot}} = 1 - \frac{T_c}{T_H} \]

ORC operational range
Efficiency if reversible
(Max. Eff.)
**Working Principles**

### The

- **Ideal Cycle:**
  - Isentropic pumping / compression (1-2)
  - Isobaric evaporation (2-5)
  - Isentropic expansion (5-6)
  - Isobaric condensation (6-1)

- **Real Cycle:**
  - **Expansion:**
    - *Heat losses, leakage, friction, over-under expansion losses → isentropic efficiency*
  - **Heat exchange:**
    - *Pressure losses, heat losses*
  - **Pumping:**
    - *Leakage, electro-mechanical losses, some supplied work is transformed in heat rather than in pressure difference → isentropic efficiency*

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*An Introduction to thermodynamics applied to Organic Rankine Cycles. Silvain Quoilin, University of Liege, 2008.*
Working Principles
The Rankine-Hirn Cycle

1-2: WF pumping to higher pressure (evaporation pressure) level (PUMP).
2-3: WF pre-heating (PREHEATER).
3-4: WF evaporation (EVAPORATOR/BOILER).
4-5: WF super-heating (SUPERHEATER).
5-6: WF expansion (EXPANDER).
6-7: WF de-superheating (DE-SUPERHEATER).
7-8: WF condensation (CONDENSER).
8-1: WF subcooling (SUB-COOLER).

\[
Q_{\text{in}} \quad \text{Heat Source IN}
\]

\[
Q_{\text{out}} \quad \text{Heat Source OUT}
\]

\[W_p \quad \text{有机流体}
\]

\[W_{\text{exp}}
\]

\[W_{\text{net}} = W_{\text{exp}} - W_p
\]

\[\eta_{\text{cycle}} = \frac{W_{\text{net}}}{Q_{\text{in}}}
\]
A single heat exchanger with the function of pre-heater, evaporator and super-heater is considered and modelled with a fixed boundaries technique, dividing the component in 3 different zones:

\[ \dot{Q}_{evap} = \dot{Q}_{preh} + \dot{Q}_{evap} + \dot{Q}_{suph} \]

where

\[ \dot{Q}_{preh} = \dot{m}_r \cdot (h_3 - h_2) \] \( \Rightarrow \) Pre-heater

\[ \dot{Q}_{evap} = \dot{m}_r \cdot (h_4 - h_3) \] \( \Rightarrow \) Evaporator

\[ \dot{Q}_{suph} = \dot{m}_r \cdot (h_5 - h_4) \] \( \Rightarrow \) Super-heater

\( \dot{m}_r \) refrigerant mass flow [kg/s]

\( h \) refrigerant specific enthalpy [J/kg]
Some Theory
Pump and Expander

- Isentropic efficiencies are considered for pump and turbine. These are calculated as follows:
  \[ \eta_P = \frac{h_{2,is}-h_1}{h_2-h_1} \]  
  \( \eta_P \) \( \Rightarrow \) Pump isentropic efficiency

  \[ \eta_E = \frac{h_5-h_6}{h_5-h_{6,is}} \]  
  \( \eta_E \) \( \Rightarrow \) Expander isentropic efficiency

- The power absorbed and generated by the pump and turbine are respectively:
  \[ \dot{W}_P = \dot{m}_r (h_2 - h_{1,is}) \frac{1}{\eta_P} \]  
  \[ \dot{W}_E = \dot{m}_r (h_5 - h_{6,is}) \eta_E \]
Some Theory

Condenser

- A single heat exchanger for the condensation phase is considered, again divided in 3 zones, and modelled using a fixed boundaries technique:

\[
\dot{Q}_{\text{cond}} = \dot{Q}_{\text{desup}} + \dot{Q}_{\text{cond}} + \dot{Q}_{\text{subcool}}
\]

where

\[
\dot{Q}_{\text{desup}} = \dot{m}_r \cdot (h_6 - h_7) \quad \Rightarrow \text{De-superheater}
\]

\[
\dot{Q}_{\text{cond}} = \dot{m}_r \cdot (h_7 - h_8) \quad \Rightarrow \text{Condenser}
\]

\[
\dot{Q}_{\text{subcool}} = \dot{m}_r \cdot (h_8 - h_1) \quad \Rightarrow \text{Sub-cooler}
\]
Improvement of the ORC
Recuperation / Regeneration

- In case of «dry fluids» utilization (ds/dT>0)
- Temperature at turbine outlet higher of condensing T
- Hot fluid can be used to pre-heat liquid
- Increase of thermal efficiency
- Decreased needed heat recovery for same power output

*An Introduction to thermodynamics applied to Organic Rankine Cycles. Silvain Quoilin, University of Liege, 2008.
• Heat exchange between two fluids is a function of $\Delta T$
• Pinch Point is the point in which $\Delta T$ is minimum
• Fundamental parameter for practical ORC design
• Must be always positive to allow heat exchange
• Smaller PP improves heat exchanger performance
• Higher PP leads to smaller and less expensive HXs
• In refrigeration 5-10 K are optimum PP considering cost-performance trade-off
• Finite PP and constant temperature evaporation/condensation increase heat transfer irreversibilities → *supercritical cycles* or *zeotropic mixtures* can improve heat transfer performance

**Subcritical vs Transcritical**

**Zerotropic mixture vs Pure fluid**
**Impiego Industriale dell’Energia**

**22 March 2017**

**ORC**

**Working Principles**

**ORC Working Fluids**

- **Refrigerants, siloxanes, alcohols, hydrocarbons** usually used for lower temperatures
  - High chemical stability temperature
  - Dry or isentropic fluids (not all)
  - High molecular mass

- Choice based on:
  - Temperatures and pressures (thermodynamic performance)
  - Toxicity
  - Flammability
  - Chemical Instability
  - Availability
  - Cost
  - Freezing temperature (low)
  - Material Compatibility
  - Environmental Impact
    - GWP (Global Warming Potential) – *ref. to CO₂*
    - ODP (Ozone Depletion Potential) – *ref. to R-11*

*www.nfpa.org*
**Working Principles**

**ORC Working Fluids**

- Medium-high temperature heat sources suitable fluids
  - *Water, alcohols (ethanol, methanol), toluene, acetone, cyclopentane...*

- Low temperature heat sources suitable fluids
  - *R245fa, isobutane, isopentane, MM, MDM, R123, R1233zd(E), R1234yf...*

- Some will be phased out due to high GWP (e.g. R245fa). Some have already been (e.g. R236fa)
## ORC Working Principles

### ORC Working Fluids

- **Medium-high temperature examples:**

<table>
<thead>
<tr>
<th>FLUID</th>
<th>CATEGORY</th>
<th>Tc [°C]</th>
<th>pc [bar]</th>
<th>Tboil, norm [°C]</th>
<th>Tf [°C]</th>
<th>NFPA</th>
<th>GWP (100)</th>
<th>ODP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water-vapour (R-718)</td>
<td>Inorganic</td>
<td>374</td>
<td>220.6</td>
<td>99.97</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>&lt;1</td>
</tr>
<tr>
<td>Ethanol (ethyl alcohol)</td>
<td>Alcohol</td>
<td>241.6</td>
<td>62.7</td>
<td>78.4</td>
<td>-114.2</td>
<td>0</td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td>Methanol (methyl alcohol)</td>
<td>Alcohol</td>
<td>239.5</td>
<td>81</td>
<td>64.5</td>
<td>-97.5</td>
<td>1</td>
<td>3</td>
<td>&lt;3</td>
</tr>
<tr>
<td>Benzene</td>
<td>Hydrocarbon</td>
<td>288.9</td>
<td>49.1</td>
<td>80.1</td>
<td>5.5</td>
<td>2</td>
<td>3</td>
<td>n.a.</td>
</tr>
<tr>
<td>Toluene (methylbenzene)</td>
<td>Hydrocarbon</td>
<td>318.6</td>
<td>41.3</td>
<td>110.6</td>
<td>-95.2</td>
<td>2</td>
<td>3</td>
<td>2.7</td>
</tr>
<tr>
<td>n-hexane</td>
<td>Hydrocarbon</td>
<td>234.7</td>
<td>30.4</td>
<td>68.7</td>
<td>-95.3</td>
<td>2</td>
<td>3</td>
<td>n.a.</td>
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<tr>
<td>n-octane</td>
<td>Hydrocarbon</td>
<td>295.2</td>
<td>25</td>
<td>125.6</td>
<td>-56.6</td>
<td>1</td>
<td>3</td>
<td>n.a.</td>
</tr>
<tr>
<td>p-xylene</td>
<td>Hydrocarbon</td>
<td>343</td>
<td>35.3</td>
<td>138.3</td>
<td>13.3</td>
<td>2</td>
<td>3</td>
<td>n.a.</td>
</tr>
<tr>
<td>Cyclohexane</td>
<td>Hydrocarbon</td>
<td>280.5</td>
<td>40.8</td>
<td>80.7</td>
<td>6.3</td>
<td>1</td>
<td>3</td>
<td>n.a.</td>
</tr>
<tr>
<td>Cyclopentane</td>
<td>Hydrocarbon</td>
<td>238.6</td>
<td>45.7</td>
<td>49.3</td>
<td>-93.5</td>
<td>1</td>
<td>3</td>
<td>n.a.</td>
</tr>
<tr>
<td>Acetone</td>
<td>Organic compound</td>
<td>235</td>
<td>47</td>
<td>56.1</td>
<td>-94.7</td>
<td>1</td>
<td>3</td>
<td>0.5</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>FLUID</th>
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<th>Tc [°C]</th>
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<th>GWP (100)</th>
<th>ODP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ethanol/Water (0.5/0.5 mass)</td>
<td>Mixture</td>
<td>339.9</td>
<td>201.2</td>
<td>81.5</td>
<td>-32</td>
<td>n.a.</td>
<td>n.a.</td>
<td>n.a.</td>
</tr>
<tr>
<td>Benzene/R123 (0.7/0.3 mass)</td>
<td>Mixture HC+Refrig</td>
<td>272.5</td>
<td>49.4</td>
<td>59.4</td>
<td>n.a.</td>
<td>n.a.</td>
<td>n.a.</td>
<td>n.a.</td>
</tr>
<tr>
<td>Cyclohexane/R123 (0.7/0.3 mass)</td>
<td>Mixture HC+Refrig</td>
<td>263.6</td>
<td>42.6</td>
<td>56.4</td>
<td>n.a.</td>
<td>n.a.</td>
<td>n.a.</td>
<td>n.a.</td>
</tr>
<tr>
<td>Cyclopentane/R123 (0.7/0.3 mass)</td>
<td>Mixture HC+Refrig</td>
<td>228.3</td>
<td>44.6</td>
<td>42.3</td>
<td>n.a.</td>
<td>n.a.</td>
<td>n.a.</td>
<td>n.a.</td>
</tr>
<tr>
<td>Pentane/Hexane (0.5/0.5 molar)</td>
<td>Mixture of HCs</td>
<td>217.7</td>
<td>32.9</td>
<td>47.9</td>
<td>n.a.</td>
<td>n.a.</td>
<td>n.a.</td>
<td>n.a.</td>
</tr>
</tbody>
</table>

- High critical temperature and pressure
- Not always low freezing point
- Often flammable (but Water...)
- Blends with water or refrigerants possible to reduce flammability
## Working Principles

### ORC Working Fluids

- **Low temperature examples:**
  - Lower critical temperature and pressure
  - Lower freezing temperature
  - Lower flammability (refrigerants)
  - High GWP – replacements with lower GWP under development

<table>
<thead>
<tr>
<th>FLUID</th>
<th>CATEGORY</th>
<th>Tc [°C]</th>
<th>pc [bar]</th>
<th>Tboil, norm [°C]</th>
<th>Tf [°C]</th>
<th>NFPA</th>
<th>GWP (100)</th>
<th>ODP</th>
</tr>
</thead>
<tbody>
<tr>
<td>R-245fa (pentafluoropropane)</td>
<td>Hydrofluorocarbon</td>
<td>154</td>
<td>36.5</td>
<td>15.1</td>
<td>-102.1</td>
<td>2</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>R-245ca (pentafluoropropane)</td>
<td>Hydrofluorocarbon</td>
<td>174.42</td>
<td>39.41</td>
<td>25.26</td>
<td>-81.7</td>
<td>2</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>R-134a (tetrafluoroethane)</td>
<td>Hydrofluorocarbon</td>
<td>101.06</td>
<td>40.59</td>
<td>-26.07</td>
<td>-103.3</td>
<td>2</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>R-236fa (hexafluoropropane)</td>
<td>Hydrofluorocarbon</td>
<td>124.92</td>
<td>32</td>
<td>-1.49</td>
<td>-93.55</td>
<td>1</td>
<td>0</td>
<td>0</td>
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<tr>
<td>Iso-pentane (R-601a)</td>
<td>Hydrocarbon</td>
<td>187.2</td>
<td>33.78</td>
<td>27.83</td>
<td>-160.5</td>
<td>1</td>
<td>4</td>
<td>-2</td>
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<tr>
<td>n-pentane (pentane, R-601)</td>
<td>Hydrocarbon</td>
<td>196.55</td>
<td>33.78</td>
<td>27.83</td>
<td>-129.68</td>
<td>1</td>
<td>4</td>
<td>-2</td>
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<td>Propane (R-290)</td>
<td>Hydrocarbon</td>
<td>96.74</td>
<td>42.51</td>
<td>-42.11</td>
<td>-187.7</td>
<td>1</td>
<td>4</td>
<td>3</td>
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<td>Isobutane (R-600a)</td>
<td>Hydrocarbon</td>
<td>134.66</td>
<td>36.29</td>
<td>-11.75</td>
<td>-159.42</td>
<td>1</td>
<td>4</td>
<td>0</td>
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<tr>
<td>MM (hexamethyldisiloxane)</td>
<td>Siloxane - Silicone oil</td>
<td>245.6</td>
<td>19.39</td>
<td>100.25</td>
<td>-0.15</td>
<td>1</td>
<td>4</td>
<td>0</td>
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<tr>
<td>MDM (octamethyltrisiloxane)</td>
<td>Siloxane - Silicone oil</td>
<td>290.94</td>
<td>14.15</td>
<td>152.51</td>
<td>-85.95</td>
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<td>0</td>
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<tr>
<td>MD2M (decamethyltetrasiloxane)</td>
<td>Siloxane - Silicone oil</td>
<td>326.25</td>
<td>12.27</td>
<td>194.36</td>
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<td>1</td>
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<tr>
<td>MD3M (dodecamethylpentasiloxane)</td>
<td>Siloxane - Silicone oil</td>
<td>355.21</td>
<td>9.45</td>
<td>229.87</td>
<td>-81.2</td>
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<td>2</td>
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<tr>
<td>D4 (Octamethylcyclosiloxane)</td>
<td>Siloxane</td>
<td>313.35</td>
<td>13.32</td>
<td>175.35</td>
<td>17.1</td>
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<td>2</td>
<td>0</td>
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<td>R141b (dichloro-1-fluoroethane)</td>
<td>Halokane</td>
<td>204.35</td>
<td>42.12</td>
<td>32.05</td>
<td>-103.5</td>
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<td>1</td>
<td>0</td>
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<tr>
<td>R123 (Dichloro-2,2,2-trifluoroethane)</td>
<td>Hydrochlorofluoro</td>
<td>183.68</td>
<td>36.62</td>
<td>27.82</td>
<td>-107.2</td>
<td>2</td>
<td>0</td>
<td>1</td>
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<tr>
<td>HFE-7000 (3M NOVEC 7000)</td>
<td>Hydrofluoroheter</td>
<td>165</td>
<td>24.8</td>
<td>34</td>
<td>-122.5</td>
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<td>0</td>
<td>370</td>
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<td>HFE-7100</td>
<td>Hydrofluoroheter</td>
<td>195.3</td>
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<td>0</td>
<td>390</td>
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<td>Ammonia (R-717)</td>
<td>Inorganic</td>
<td>132.25</td>
<td>113.33</td>
<td>-33.33</td>
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<td>CO2 (R-744)</td>
<td>Inorganic</td>
<td>31.06</td>
<td>73.8</td>
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<td>-56.6</td>
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<td>0</td>
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<tr>
<td>COMMERCIAL</td>
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<td></td>
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<tr>
<td>Solkatherm (SES36)</td>
<td>Commercial/Mixture</td>
<td>177.6</td>
<td>28.5</td>
<td>36.7</td>
<td>n.a.</td>
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<td>3</td>
<td>1</td>
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<tr>
<td>3M Novec-649</td>
<td>Commercial</td>
<td>169</td>
<td>18.8</td>
<td>49</td>
<td>n.a.</td>
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<td>0</td>
<td>1</td>
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<tr>
<td>NEW (in development)</td>
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<tr>
<td>R-1234yf (tetrafluoroethene)</td>
<td>Hydrofluoroolefin</td>
<td>94.7</td>
<td>33.8</td>
<td>-29.45</td>
<td>-53.15</td>
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<td>R-1234ze(E) (tetrafluoroethene)</td>
<td>Hydrofluoroolefin</td>
<td>109.36</td>
<td>36.35</td>
<td>-18.97</td>
<td>-104.5</td>
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<td>R-1336mzz-Z</td>
<td>Hydrofluoroolefin</td>
<td>171.3</td>
<td>29</td>
<td>33.4</td>
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<td>n.a</td>
<td>n.a.</td>
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<td>R-1233zd(E)</td>
<td>Hydrofluoroolefin</td>
<td>165.6</td>
<td>35.7</td>
<td>18.3</td>
<td>n.a.</td>
<td>2</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
Main Components
Heat Exchangers

- Shell & Tube
- Plate HX
- Fin & Tubes / Fin and Plates

- Heat transfer performance
- Pinch Point
- Cost
- Size
- Corrosion
- Fouling

*Bowmann

*GEA

*BEHR/MAHLE

*ALFA LAVAL Aalborg pressurized EGR cooler (mainly for big Rankine Steam ship applications)
Main Components
Pumps

- Some examples:

- HYDRA CELL (diaphragm)
- VIKING PUMP (Gear)
- GRUNDFOS (Centrifugal)
- Fluid-o-Tech (Rotary Vane) – small applications
- SIHI (sealless centrifugal pumps – also with magnetic coupling)
- CAT (diaphragm pumps – high temperature suitable)
Main Components

Pumps

- Possible suitable solution are Centrifugal Pumps, Diaphragm Pumps or Rotary vane
- Inverter coupling to control the pump rotating speed and the working fluid massflow rate
- Used to control also evaporation pressure
- Leakage must be prevented
- Low BWR (Back Work Ratio) required: \[ BWR = \frac{W_{pump}}{W_{exp}} \]
- Avoid cavitation (e.g. gravity fed working fluid pump solution adopted by Turboden in large size systems)
- Efficiency should be at least 60%
- Tank collecting condensed working fluid
Main Components
Expanders

- Choice of expansion machine critical for Rankine cycle based WHR system success
- Two main categories under which a number of basic operating principles can be classified:
  - Positive displacements machines
    - Reciprocating piston machines
      - crosshead
    - Rotary ‘piston’ machines
      - vane-type
      - Wankel-type
      - scroll-type
      - screw-type (Lysholm)
  - Continuous flow machines
    - Turbines (reaction or pressure type)
      - radial
      - axial

Turbine Expanders (Radial and Axial) are more suitable for bigger dimensions ORC systems (e.g. Big Marine Engines WHR Applications >50-100 kW)
Main Components

Expanders

- Reciprocating piston
  - Similar to combustion engine
  - Alternatives:
    - crosshead
    - controlled valves
    - automatic (reed) valves
  - Challenges:
    - package
    - lubrication
    - vibration
    - wear
Main Components

Expanders

- **Vane-type**
  - Single acting (left) or double acting (right)

- **Main issues:**
  - sealing
  - lubrication
Main Components

Expanders

- **Wankel-type**
  - Implemented both as air compressor and combustion engine
  - Potentially only rotating parts
  - Two-stroke versions (right) preferable

- Sealing issue
Main Components

Expanders

- **Scroll-type**
  - Only low pressure ratio possible - hence, low temperature ratio
  - Overexpansion & Underexpansion losses
  - Sealing / leakage losses
  - Lubrication vs non-lubrication
  - Small scale ORCs
Main Components

Expanders

- **Screw-type (Lysholm)**
  - Implemented mainly as (silent) air compressor
  - Sealing oil issue
  - Small to medium size applications
Main Components

Expanders

- **Radial turbine**
  - Back-pressure (non-condensing)
  - Single stage
  - Especially for higher power systems (more than 50 kW – **Marine Applications**)
  - Need of no liquid presence in turbine (damaging problems)
  - High expansion ratios
  - Choking problems
  - Must be designed for the operational point
**Main Components**

**Expanders**

- **Axial turbine**
  - Reaction type
  - Single stage
  - Higher power systems (*Marine*)

Source: Techno-economic survey of ORC systems (*Quoilin*)
Contents

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• Working Principles
• Efficiency Comparison
• Applications
• Conclusions
Efficiency Comparison

https://csiropedia.csiro.au/ceramic-fuel-cells/
Contents

- Introduction
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Applications Biomass

Biomass Combined Heat and Power (CHP) Station
With a consumption of 40,000 tonnes wood or other biomass, a 5 MW class combined heat and power (CHP) station generates around 30 million kilowatt-hours electricity and 50 million kilowatt-hours heat annually. In principle, such a power station functions like a coal-fired power station.

- Biomass availability
- Medium-small size distributed CHP systems

*Stefano Clemente, Rodolfo Taccani, Impiego Industriale dell’Energia
Applications

Solar

- Concentrated solar power plants
- Solar fields
- Smaller solar thermal applications

*Review or organic Rankine cycle for small-scale applications. Rahbar et al., Energy Conversion and Management, 2017

*Stefano Clemente, Rodolfo Taccani, Impiego Industriale dell’Energia

*Rodolfo Taccani, Brighton 2016 – University of Trieste/Kaymacor system for solar application
Applications Geothermal

- Small or high power geothermal applications
- Very low temperature applications

*Review or organic Rankine cycle for small-scale applications. Rahbar et al., Energy Conversion and Management, 2017

*Exergy Geothermal ORC plant with radial inflow turbine
Applications
Micro-cogeneration

- Isolated systems
- Residential systems
- Possibility of trigeneration (cold production)
- Possible synergy with renewable systems (storage, solar, small geothermal, small biomass)
- Recuperation from small GT and ICE

*Stefano Clemente, Rodolfo Taccani, Impiego Industriale dell’Energia

*Kaymacor – University of Trieste collaboration
Applications
Micro-cogeneration – University of Trieste experience

Full scale ORC test bed

*Main specs:*
Flow rate: up to 600 kg/h with R245fa
Operating pressure: 25 bar
Flow rate measurement: multi phase flow meter
Heat capacity: up to 80 kWt

- Test bench and prototypes development (<10 kW size)
- Thermal-oil hot loop
- Scroll expansion machine
- Plate heat exchangers
- Fluid: R245fa (R1233zd(E))
- Gear-pump test bench
Applications
Waste Heat Recovery – Bottoming Cycles

**Turboden 7 CHP**
*Net electric power: 702 kW*
*Net electric efficiency: 18%*
*Heat source $T$: 240 – 300 °C*
*Heat sink $T$: 60 – 80 °C*

- Main example is the CCGT
- Recovery from «topping cycles»
  - ICE
  - Stationary Power Generation
  - Marine Applications
  - Industrial Waste Heat
- Diathermic Oil loop or pressurized water as heat carrier

*Stefano Clemente, Rodolfo Taccani, Impiego Industriale dell’Energia*
Typical Marine HDDE Heat Balances

- Wärtsilä 6RT-flex58T-D (13.6 MW – 2 stroke propulsion engine – 100% Load – ISO Conditions)

- Wärtsilä W6L20 (1.2 MW – 4 stroke auxiliary power generator – 100% Load)

Source(WinGD, GTD)

Source(Wärtsilä, 20 Product Guide)
## Typical Marine HDDE Temperatures

<table>
<thead>
<tr>
<th>Heat Source / Sink</th>
<th>4-Stroke</th>
<th>2-Stroke</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exhaust Gas Temperature (AT) [°C]</td>
<td>300-500</td>
<td>250-300</td>
</tr>
<tr>
<td>Cooling Water Jacket Temperature (HT) [°C]</td>
<td>80-90</td>
<td>80-90</td>
</tr>
<tr>
<td>Scavenge Air Cooler Cooling Circuit Temperature (LT) [°C]</td>
<td>/</td>
<td>25-36</td>
</tr>
<tr>
<td>CAC Cooling Circuit Temperature (LT) [°C]</td>
<td>40-65</td>
<td>/</td>
</tr>
<tr>
<td>Lube Oil Circuit [°C]</td>
<td>65-80</td>
<td>60-75</td>
</tr>
<tr>
<td>Sea Water [°C]*</td>
<td>Up to 30-40</td>
<td></td>
</tr>
<tr>
<td>Cooling Air [°C]**</td>
<td>Up to 40-45</td>
<td></td>
</tr>
</tbody>
</table>

* Depending on Sea Water temperature, Usually average see temperature considered around 22°C with a good safety margin for WHR cooling design purpose

** Depending on Ambient Air temperature, On board Air conditioning and ventilation systems
Applications
Automotive

- Challenging applications due to the transient operating profile / cooling
- HD trucks & Commercial Vehicles main application
- Pass Cars under development

Cummins:
- Layout: Exhaust + EGR (mostly) in series in one circuit with recuperator
- Other layouts with CAC also studied (or EGR only)
- Working fluid: R245-fa
- Evaluation of radial and axial expanders
- Mechanical coupling
**ORC Applications**

**Marine**

- 2-stroke or 4-stroke marine engine WHR
- High temperature exhaust gas or lower temperature heat recovery (Coolant, Intake air cooling)
- Potential for further R&D
- Actual low marine fuel cost discourages use

<table>
<thead>
<tr>
<th>Testing Results for 30 MW engine WHR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exp. Inlet Pressure</td>
</tr>
<tr>
<td>Exp. Inlet Temperature</td>
</tr>
<tr>
<td>WF Flowrate</td>
</tr>
<tr>
<td>Net Generated Power</td>
</tr>
<tr>
<td>Net Efficiency</td>
</tr>
<tr>
<td>IPM Isentropic Efficiency</td>
</tr>
<tr>
<td>Turbine Rot. Speed</td>
</tr>
</tbody>
</table>

*Calnetix*
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Conclusions

- ORC: electrical energy production, especially in CHP applications
- Heat recovery of low temperature applications the new challenge
- Large stationary applications well proven technology (up to MW size)
- «Simple Rankine Cycle» is the baseline, however ORC technology, especially for smaller applications, is not yet mature:
  - Working Fluid
  - Efficient components (expansion machines efficiency to be improved)
- The technology must be improved:
  - Efficiency / Components
  - Cost
- Cheaper prototypes can be developed from similar technologies, especially for small plants (HVAC)
- Still room for R&D available
  - Small distributed or residential CHP applications
  - Marine / Automotive
ORC

Research Material Suggestions