Selection Maps For ORC And CO$_2$ Systems
For Low-Medium Temperature Heat Sources

Marco Astolfi, Silvia Lasala, Ennio Macchi
Professor Angelino was one of the father of both ORC and sCO$_2$ technologies.

In the second half of last century the pioneering studies of Professor Angelino set the standard for:

- fluid selection criteria and effect on turbomachinery design for ORC field
- Best cycle configurations and optimal design for sCO$_2$ power systems

The results obtained in those studies are the reference benchmark still today.
Until recent years ORC and sCO$_2$ cycles have been studied for two completely different application fields as alternative for steam power plants:

**ORC**
- **Low temperature** heat sources like geothermal energy, solar energy with low concentrating ratio and OTEC systems
- **Small available heat** like in civil and domestic cogeneration, small WHR application and biomass

**sCO$_2$**
- **High temperature** and **Large available heat** applications like nuclear, solar towers and recently fossil fuels
INTRODUCTION (3)
...to the need of clarity

**ORC**
- **Low temperature** heat sources like geothermal energy, solar energy with low concentrating ratio and OTEC systems
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**sCO₂**
- **High temperature** and **Large available heat** applications like nuclear, solar towers and recently fossil fuels

Nowadays the scenario is **strongly changed**:
- Many organic fluids for ORC applications are going through a **phase out** process because of their environmental impact (high **GWP**) or safety reasons (flammability and toxicity)
- sCO₂ is experiencing **large investments** mainly driven by CSP field that will bring soon this technology to a **mature technological level**
As result this division will become more and more blurred in future years with ORC and sCO$_2$ power plants **competing** in a large range of applications

- Large biomass plant
- Large and high temperature WHR (glass, steel, cement industries)
- Medium size CSP plant based mainly based on linear concentrators

As result a NEW **GREY ZONE** is coming
>> WORK BASIS
Aim of the study and General approach

Our goal:
• Understanding which is the most suitable solution among ORC and sCO\textsubscript{2} for different energy sources and applications
• providing decision maps for the correct choice of the best plant from a thermodynamic point of view

Our approach:
• We defined the optimal ORC and optimal sCO\textsubscript{2} cycle for a large range of energy sources differing in:
  ➢ maximum temperature (250°C – 600°C)
  ➢ cooling grade (0% - 100%)

△\textit{T}\% = \frac{(T_{s,max} - T_{s,min})}{(T_{s,max} - T_0)}

• Available power is fixed and equal to 30 MW with reference to medium- large size applications
• Two cases are investigated: air and water cooled plants with possibility to condensate CO\textsubscript{2}
This allows to represent both nearly isothermal heat sources and finite heat capacity heat sources with technical limits in the minimum temperature.

<table>
<thead>
<tr>
<th>Heat source</th>
<th>T_{min,s} °C</th>
<th>200</th>
<th>250</th>
<th>300</th>
<th>350</th>
<th>400</th>
<th>450</th>
<th>500</th>
<th>550</th>
<th>600</th>
</tr>
</thead>
<tbody>
<tr>
<td>0%</td>
<td></td>
<td>200</td>
<td>250</td>
<td>300</td>
<td>350</td>
<td>400</td>
<td>450</td>
<td>500</td>
<td>550</td>
<td>600</td>
</tr>
<tr>
<td>20%</td>
<td></td>
<td>163</td>
<td>203</td>
<td>243</td>
<td>283</td>
<td>323</td>
<td>363</td>
<td>403</td>
<td>443</td>
<td>483</td>
</tr>
<tr>
<td>40%</td>
<td></td>
<td>126</td>
<td>156</td>
<td>186</td>
<td>216</td>
<td>246</td>
<td>276</td>
<td>306</td>
<td>336</td>
<td>366</td>
</tr>
<tr>
<td>60%</td>
<td></td>
<td>89</td>
<td>109</td>
<td>129</td>
<td>149</td>
<td>169</td>
<td>189</td>
<td>209</td>
<td>229</td>
<td>249</td>
</tr>
<tr>
<td>80%</td>
<td></td>
<td>52</td>
<td>62</td>
<td>72</td>
<td>82</td>
<td>92</td>
<td>102</td>
<td>112</td>
<td>122</td>
<td>132</td>
</tr>
<tr>
<td>100%</td>
<td></td>
<td>15</td>
<td>15</td>
<td>15</td>
<td>15</td>
<td>15</td>
<td>15</td>
<td>15</td>
<td>15</td>
<td>15</td>
</tr>
</tbody>
</table>

- Geothermal brine (silica deposition)
- Solar HTF (pouring issues)
- Flue gases (acid condenses)
- Isothermal sources
4 Cycle configurations:
saturated and superheated subcritical with or without recuperator

47 working fluids:
15 alkanes, 8 other HC, 16 halogenated, 8 siloxanes

Large range of critical temperatures and molecular complexity
Maximum temperature is set by thermal stability limit or lack of experimental data.
Minimum pressure is set to 1 bar in order to avoid air leakage

Optimization variables $T_{eva}$, $T_{cond}$, $T_{inTurbine}$
Recompressed cycle allows to limit the temperature differences in the recuperative process.

Water cooled plant allows for CO$_2$ condensation leading to an increase of power output.

Optimization variables $p_{\text{max}}$ (UB=300bar), $p_{\text{min}}$, split ratio.
## DESIGN CRITERIA

### Common Assumptions

<table>
<thead>
<tr>
<th></th>
<th>CO₂</th>
<th>ORC</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Heat sink temperature</strong></td>
<td>15°C water cooled, 25°C air cooled</td>
<td>15°C water cooled, 25°C air cooled</td>
</tr>
<tr>
<td><strong>Minimum working fluid temperature</strong></td>
<td>25°C</td>
<td>25°C</td>
</tr>
<tr>
<td><strong>ΔT_{ap,PHE}, ΔT_{pp,PHE}, ΔT_{pprec}</strong></td>
<td>10°C</td>
<td>5°C</td>
</tr>
<tr>
<td><strong>ΔT_{subcooling}</strong></td>
<td>-</td>
<td>5°C</td>
</tr>
<tr>
<td><strong>Δp (or, whether relative, Δp/ρ_{in}) PHE</strong></td>
<td>2%</td>
<td>50kPa (ECO), ΔT=1°C (EVA), 2% (SH)</td>
</tr>
<tr>
<td><strong>Δp (or, whether relative, Δp/ρ_{in}) REC</strong></td>
<td>2% (hot side), 2% (cold side)</td>
<td>2% (hot side), 50 kPa (cold side)</td>
</tr>
<tr>
<td><strong>Δp (or, whether relative, Δp/ρ_{in}) HR</strong></td>
<td>2%</td>
<td>2% (desuperheating), ΔT=0.5°C (condensation)</td>
</tr>
<tr>
<td><strong>Compressor/pump hydraulic efficiency</strong></td>
<td>0.85</td>
<td>0.97</td>
</tr>
<tr>
<td><strong>Generator electrical efficiency</strong></td>
<td></td>
<td>0.97</td>
</tr>
<tr>
<td><strong>Mechanical efficiency</strong></td>
<td></td>
<td>0.97</td>
</tr>
<tr>
<td><strong>Pump electrical motor efficiency</strong></td>
<td>0.97</td>
<td>0.97</td>
</tr>
<tr>
<td><strong>Auxiliaries consumption loss</strong></td>
<td>2%</td>
<td></td>
</tr>
</tbody>
</table>

Turbine efficiency is computed as function of SP and Vr
• Power production is higher for high temperature heat sources with a low cooling grade,
• Power production is limited for heat sources temperatures higher than 450°C because of the fluid thermal stability limit
• Power production is lower for air cooled plants because of the higher condensation temperature
Best fluid critical temperature increases with the heat source temperature and for nearly isothermal heat sources:

- 16 – R236ea 139°C
- 22 – neo pentane 161°C
- 23 – cis butene 163°C
- 25 – iso pentane 187°C
- 26 – pentane 197°C
- 29 – cyclo pentane 239°C
- 32 – cyclo hexane 280°C
- 33 – benzene 289°C
Superheated recuperative cycle is always convenient however:

- saturated cycles can be competitive for low temperature sources with small cooling grade
- Recuperator is not convenient for low-medium temperature heat sources with high cooling grades (marked with * )
• Power production always increases reaching thanks to CO₂ stability at high temperatures
• Power production strongly penalized for air cooled plants because condensation is not possible. Positive net power is obtained for heat sources temperatures higher than 300°C
Recycled cycle (R) performs better than simple recuperative cycle (S) for high temperatures and nearly isothermal heat sources.

The advantages in adopting a more complex configuration are limited and the two cycles have similar power outputs (2% difference) in the shaded area.
• For water condensed cycles ORC are recommended for:
  • heat sources temperatures below 350°C
  • for hotter heat sources having high cooling grades thanks to their ability to recover heat at low temperatures
• sCO₂ cycles are more efficient for high temperatures thanks to the increase of turbine power output respect to the compressor consumption

• Air cooling strongly penalizes sCO₂ that becomes convenient only for a very limited number of applications
CONCLUSIONS
based on preliminary results

- sCO$_2$ cycles are certainly a reliable option for high temperature large power plants while they must compete with ORC in other applications.
- Performances attainable by sCO$_2$ also at lower temperatures and for medium size application can be attractive especially in presence of particular constraints related to safety.
- Excluding flammable and toxic fluids CO$_2$ prevails also at low temperature (350°C) and high cooling grades.

- Analysis should be extended to other sCO$_2$ plant configurations.
- Analysis should be extended to economic analysis in order to catch the reduction of power plant capital cost allowable with compact CO$_2$ cycles.
IV International Seminar on ORC Power Systems

THANKS FOR THE ATTENTION

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