Solar-based ORC power systems

by Rémi Dickes
Context

Solar Thermal Power:

Organic Rankine cycle

Ivanpah CSP plant (392 MWe)

< 1 MWₑ

1 MWₑ

10 MWₑ

100 MWₑ

1000 MWₑ

Steam Rankine cycle

Ivanpah CSP plant (392 MWe)

Solar field

Power Unit

Thermal Energy Storage

STG CSP plant (3kWe)
- 1st operational ORC
- Built by Frank Shuman
- Philadelphia (USA), 1907
- “Hot box” collector, 100 m²
- Direct vapor of ether at 115°C
- 2.5 kW ORC
- Irrigation pump

Ref: [1]
Presentation structure

1. Organic Rankine Cycle
2. Solar field and collectors
3. Thermal energy storage
4. Fields of application
5. Modelling tools
2. Organic Rankine Cycle
Rankine cycle – the basics

Thermodynamic cycle in 4 steps:
- 1-2 : liquid compression ($P_{\text{low}} \rightarrow P_{\text{high}}$)
- 2-3 : evaporation (Liquid → Vapor)
- 3-4 : vapor expansion ($P_{\text{high}} \rightarrow P_{\text{low}}$)
- 4-1 : condensation (Vapor → Liquid)

Result: $\dot{W}_{\text{net}} = \dot{W}_{\text{exp}} - \dot{W}_{\text{pp}} > 0$

Working medium: water … or organic fluid
Why going organic?

+ Dry expansion $\rightarrow$ no need for superheating
+ Lower boiling point $\rightarrow$ permit to apply Rankine cycle with low temperature heat source
+ Lower evaporating pressure $\rightarrow$ safer and less complex
+ Simpler boiler architecture $\rightarrow$ no need of steam drum + recirculation (single HEX ok)
+ Higher density at same condensing temperature $\rightarrow$ smaller components size
+ Supatmospheric condensing pressure $\rightarrow$ no infiltration

- Higher relative pump consumption (Back Work Ratio)
- Fluid characteristics (cost, availability, safety properties)
- Lower thermal efficiency

ORC suitable for low temperature OR/AND small capacity systems
Organic fluids

- Organic fluid = contains Carbon → very large variety (CFC, HFC, HCFC, HC,…)
- Proper fluid selection is among the most important design parameter
- Common working fluid in experimental facilities:
  - R134a
  - R245fa
  - SES36
  - n-pentane
  - Toluene

- Characteristics to account for:
  - Thermodynamic performance
  - High vapor density (component size)
  - Acceptable evaporating pressure (safety)
  - Condensing pressure > 1 atm (infiltration)
  - Temperature stability
  - Melting point (vs. $T_{amb}$)
  - Toxicity/Flammability
  - ODP/GWP
  - Cost, availability
  - Integration with components
Expansion devices

Positive-displacement expander

- Low rotational speed
- Wet expansion
- Availability (e.g. HVAC)
- Cost

  - Fixed built-in $r_v$
  - Limitation in supply conditions (T/P)

  Low capacity ORC (<50 kWe)

 Scroll [0.1-10 kW]
 Screw [5-100 kW]
 Piston [1-20 kW]

Turbomachinery

- Compactness/weight
- High efficiency
- Off-design performance

- High rotational speed
- Design complexity
- Dry expansion only

Axial [1kW -1MW]
Radial

High (... and low) capacity ORC
Expansion devices

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- Scroll
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High (... and low) capacity ORC

- Fixed built-in \( r_v \)
- Limitation in supply conditions (T/P)

Low capacity ORC (<50 kWe)
Operating conditions

Screw expander (n-pentane)

Boundary limits:

1. $T_{ev} < T_{cd}$
   Pressure ratio > 1

2. $T_{ev} > T_c$
   Subcritical ORC

3. $\varepsilon_{in} < 0.9$
   Limited under/over expansion losses

4. $VC > 0.5$

See Ref [2] for further information
Operating conditions

Screw expander

Scroll expander

Turbine

See Ref [2] for further information
System architecture

Recuperative ORC

- $\epsilon_{\text{ORC}}$
- $\eta_{\text{SF}}$
- $? \epsilon_{\text{net}}$

Cascaded expansion

- $Rv_{\text{tot}} = rv_1 \times rv_2$
- Lower expansion losses
- Careful with design!

Parallel expansion

- 3 modes:
  - Big expander
  - Small expander
  - Both
- Better compliance of expanders performance in part-load conditions
Solar field \rightarrow Thermal Energy Storage \rightarrow ORC \rightarrow Solar field
4. Solar field and collectors
Solar collectors

- Non-concentrating collectors
  - Flat Plate Collectors (FPC)
  - Evacuated Tube Collectors (ETC)
  - Salt-Gradient Solar Pond (SGSP)

- Concentrating collectors
  - Compound Parabolic Collector (CPS)
  - Linear Fresnel Collector (LFC)
  - Parabolic Trough Collector (PTC)
  - Parabolic Dish Reflector (PDR)
  - Solar Central Tower (SCT)
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Power plant example
- Borj Cedria, Tunisia (1982)
- 760 m² of FPCs
- Water at 98 °C
- 16 kWe ORC unit (Turboden)
- Single stage turbine
- WF : C₂Cl₄

Ref: [3]
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Power plant example

- Busan, Korea (2015)
- 33 m² of ETCs
- Water at 120 °C
- 1.5 kWe ORC unit (R&D)
- R245fa
- Scroll expander

Ref: [4]
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Power plant example
- El Paso (Texas), USA (1986)
- 3300 m² solar pond (3.2m depth)
- Brine at 90°C
- 100 kWe ORC unit (Ormat)

Ref: [5]
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Power plant example
- Miyagi, Japan (2005)
- 5.75 m² CPC
- Water at 140 °C
- 0.5 kWe ORC unit (R&D)
- R113 (despite of high ODP..)
- Scroll expander

Ref: [6]
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Power plant example
- Ottana (Sardinia), Italy (2015)
- 8400 m² Frena LFC
- Diathermic oil at 260 °C
- 600 kWe ORC unit (Turboden 6HR)

Ref: [7]
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Power plant example: Sun2Power
- University of Liège, Belgium (2016)
- 70 m² PTC (T13 from STG International)
- Thermal oil at 175°C (2bar)
- 3 kWe ORC unit (R&D from ULg)
  - R245fa
  - Scroll Expander
  - Air-cooled condenser
  - CPHEX, recuperative ORC

Ref: [8] + www.sun2power.eu
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Power plant example
- Pasadena (California), USA (1978)
- 117 m² of PDR
- Direct steam generation (Toluene) at 420 °C
- 30 kWe ORC unit (R&D)

Ref: [9]
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Power plant example
- Kamboinsé, Burkina Faso (2016)
- 180 m² of heliostats
- Vegetable oil at 200 °C
- 10 kWe ORC unit (Infinity Turbine)

Ref: [10]
Solar field architecture

**Direct Vapor Generation**

- Avoid one heat delivery HEX
- No parasitic pump losses
- Simple architecture
- High-pressure in solar receiver
- Larger volume of costly/unsafe WF

**Intermediate Heat Transfer Fluid**

- Low-pressure in solar receivers
- Higher safety and control
- Additional HEX
- Parasitic pump consumption

- Small-scale (domestic) systems
- Parabolic dish / Flat plate collector

- Medium- and large scale systems
- Linear collectors (CPC/PTC/LFC)
  - **Proper selection of HTF**

- Water
- Thermal oil
4. Thermal Energy Storage
Thermal Energy Storage

- Sensible TES
- Latent TES
- Thermochemical TES
Thermal Energy Storage

- **Sensible TES**
- **Latent TES**
- **Thermochemical TES**

Sensible thermal energy storage

Single buffer:

- $\rho_{\text{TES}} \sim \text{kJ/m}^3$
- Possibility of filler material

Two-tank direct

Two-tank indirect

Thermocline direct

Thermocline indirect
Latent thermal energy storage

\[ A_{\text{phase},1} \leftrightarrow A_{\text{phase},2} \]

- Mostly solid-liquid phase-change
- Often with encapsulation (avoid mixing with HTF)
- Higher energy density ($\rho_{\text{TES}} \sim \text{MJ/m}^3$)
- Quasi-isothermal process
- Change in thermal conductivity (dis/charging time)
- Storage media:
  - Organic: paraffins/ fatty acids
  - Inorganic : salt hydrates
  - Eutectic mixtures
Thermal Energy Storage

- Sensible TES
- Latent TES
- Thermochemical TES

Thermochemical thermal energy storage

\[ AB \leftrightarrow A + B \]

- Highest energy density \((\rho_{\text{TES}} \sim \text{GJ/m}^3)\)
- Quasi-isothermal process
- Storage at ambient temperature \(\rightarrow\) lossless
- Large temperature range of application

- Examples:

<table>
<thead>
<tr>
<th>Chemical reaction</th>
<th>Temperature range</th>
<th>Energy density</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\text{FeCO}_3 \leftrightarrow \text{FeO} + \text{CO}_2)</td>
<td>180 °C-200°C</td>
<td>2.6 GJ/m³</td>
</tr>
<tr>
<td>(\text{CH}_3\text{OH} \leftrightarrow \text{CO} + 2\text{H}_2)</td>
<td>200°C - 250°C</td>
<td>-</td>
</tr>
<tr>
<td>(\text{Ca(OH)}_2 \leftrightarrow \text{CaO} + \text{H}_2\text{O})</td>
<td>400 °C-600°C</td>
<td>3 GJ/m³</td>
</tr>
<tr>
<td>(\text{CaCO}_3 \leftrightarrow \text{CaO} + \text{CO}_2)</td>
<td>800°C -900 °C</td>
<td>4.4 GJ/m³</td>
</tr>
<tr>
<td>(6\text{Mn}_2\text{O}_3 \leftrightarrow 4\text{Mn}_3\text{O}_4 + \text{O}_2)</td>
<td>900°C-1000°C</td>
<td>1 GJ/m³</td>
</tr>
</tbody>
</table>
5. Fields of application

- Solar field
- Thermal Energy Storage
- ORC

Diagram showing the interconnection between solar field, thermal energy storage, and ORC.
Application – Power Generation

Grid-connected power generation:

- Small-scale solar ORCs are unlikely to be developed for grid-connected generation
- CSP for grid-scale application is more attractive with high capacity and high temperature systems (steam, Brayton or sCO$_2$)

- Two examples:
  - Beith Ha’Arava (Dead Sea), Israel
    - 1985-1986 (continuously) – stop in 1989
    - 250 000 m$^2$ solar pond (brine water at 95°C)
    - 5 MWe ORC unit (Ormat)
    - Ref: [11]
  - Saguaro (Arizona), USA
    - 2006-Now
    - 10300 m$^2$ of PTC (thermal oil at 300 °C)
    - 1 MWe ORC unit (Ormat)
    - n-pentane
    - Ref: [12]
Application – Power Generation

Distributed power generation:

- Small solar ORCs much more competitive:
  - Robustness and ease of local development/exploitation
  - Mass manufactured component from HVAC industry
  - Polygeneration (mechanical power, electricity, hot, cold)
  - Storage + control → good dispatchability
  - Hybridizing with local biomass or genset WHR

- Example of one STG International* power system:
  - Matjotjo Village, Lesotho
  - 70 m² PTC field + 3 kWe ORC unit (MEG at 150°C)
  - Single buffer TES
  - R245fa with scroll expander
  - Health clinic with 50-80 partients
  - 24 kWhₑ and 380 m³ hot water per day
  - Ref: [13]

* http://www.stginternational.org
Fields of application - Desalination

Desalination (or water purification)

- ORC + Reverse Osmosis (RO) system

- Example
  - Marathon, Greece
  - 216 m² of ETC (water at 78°C)
  - 2.5 kW ORC with R134a
  - Single scroll expander
  - RO unit 0.3 m³/h of fresh water (15% recovery)
  - Ref: [14]
Fields of application - Irrigation

- ORC + irrigation water pump
- Good match between solar resource and irrigation requirements
- Examples
  - Coolidge, Arizona (USA)
  - 1972-1982
  - 2140 m² PTC (thermal oil at 288°C)
  - 200 kWe ORC unit
  - Toluene, turbine, 20% net
  - Ref: [15]
  - Gila Bend, Arizona (USA)
  - 1977
  - 537 m² PTC (water at 155°C)
  - 37 kWₘ ORC unit
  - R113, turbine
  - Ref: [16]
Fields of application – Hot / Cold generation

- Hot generation: solar collectors / condenser heat recovery
- Cold generation: ORC + ejector
- Hybrid CHP systems: ORC/HP/direct heating

Ref: [17]
Fields of application – Hybridizing

Industrial WHR-solar ORC

Example:

- Aït Baha, Marocco
- 6200m² PTC (air at 600°C)
- 2 MWe (Turboden 18HR)
- Fluid : HMDS
- Air-cooled condenser
- TES : Sensible (12hours)

- Ref: [18]
Fields of application – Hybridizing

Geothermal-solar ORC

Example:

- Stillwater hybrid geothermal-solar power plant
- Fallon, Nevada (USA)
- 2 MWe CSP + 33 MWe geoth. + 26 MWe PV
- 660 m² of PTC (water at 155°C)
- WF: Isobutane
- Air-cooled / 4 turbines

Ref: [19]
Fields of application – Hybridizing

Biomass-solar ORC

Example:

- Rende CSP-biomass power plant (Italy)
- Retrofit of existing 14 MWe biomass ORC with CSP (total 15 MWe)
- 9800 m² of LFC (thermal oil at 280°C)
- No information on the ORC (?)
- No TES

- Ref: [20]
6. Modelling tools
Modelling tools

- Modelling crucial in
  - Thermo-economic studies
  - System design and sizing optimization
  - Off-design performance assessment
  - Control definition

- Major distinction between
  - Steady-state modelling: equilibrium conditions
  - Dynamic modelling: accounts for mass and energy accumulation in transients operation

- Time consuming process for model development but open-access libraries exist
Modelling tools – Steady-state modelling

‘ORCmKit’ modelling library

- Open-source modelling library dedicated to ORCs
- Initiated by ULg and UGhent but aimed for entire community
- 3 modelling platform: EES/Python/Matlab
- Models for HEX, expander, pump, pipelines, ORC,…
- Calibration and graphical tools
- Reference:
  - https://github.com/orcmkit/ORCmKit
  - Dickes et al., 2016. ORCmKit: an open-source library for organic Rankine cycle modelling and analysis, in: Proceedings of ECOS 2016, Portoroz (Solvenia), 2016. (ref: [21])
Modelling tools – Dynamic modelling

‘ThermoCycle’ Modelica library

- Open-source Library for the modelling of thermal systems (including SORCs)
- Software: Dymola (Modelica language)
- Special focus on thermodynamic cycles
- Component and cycle models available
- Cross-Platform
- Computational efficiency and robustness
- Websites: thermocycle.net modelica.org/libraries
Thanks for your attention
Any questions?

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This presentation is mainly inspired by the following chapter co-written by the author:

External references presented along the presentation are listed here under:


[18] “Al-Baha CSP plant brochure.”

