Experimental investigation into an ORC-based low-grade energy recovery system equipped with sliding-vane expander using hot oil from an air compressor as thermal source

Stefano Murgia¹, Gianluca Valenti², Daniele Colletta¹, Ida Costanzo¹, Giulio Contaldi¹
Introduction

ORGANIC RANKINE CYCLE (ORC)

Widespread technology for electric power production using low-grade heat source

Different low-grade energy sources

- Biomass: 76.5%
- Geothermal: 12.7%
- Solar: 10.7%
- Other: 0.1%

ORC sources market share (from orc-world-map.org 21/01/2016)

Several applications fields for heat recovery

- Diesel engine or gas turbine: 66.8%
- Landfill gas engine: 0.9%
- Chemical industry: 0.9%
- Biogas: 1.0%
- LPG: 1.4%
- Petroleum and coal products: 1.4%
- Glass: 5.0%
- Waste to energy: 5.8%
- Primary or fabricated metals: 7.2%
- Cement & lime: 8.3%

ORC heat recovery share (from orc-world-map.org 21/01/2016)
Context

SMALL SCALE ORC (few kilowatts)

Oil-flooded air compressor

Large amount of lubricant that need to be cooled down

WASTE HEAT SOURCE with temperatures in the range 80-100°C

POSITIVE DISPLACEMENT EXPANDERS

Sliding-vane expander features:

• relatively low rotational speed
• high expansion ratio
• smooth torque
• low noise and vibration
• simple structure and no valves
• need for lubrication

<table>
<thead>
<tr>
<th></th>
<th>Displacement</th>
<th>Built-in volume ratio</th>
<th>Rotor length</th>
<th>Rotor diameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simple cycle expander</td>
<td>26.5 cm³</td>
<td>3.34</td>
<td>160 mm</td>
<td>80 mm</td>
</tr>
<tr>
<td>Recuperative cycle expander</td>
<td>19.95 cm³</td>
<td>2.76</td>
<td>90 mm</td>
<td>100 mm</td>
</tr>
</tbody>
</table>
System layouts

Simple cycle

- Working fluid: R236fa
- Hot source: Air compressor lubricant
- Cold source: Water

Recuperative cycle

- Working fluid: R236fa
- Hot source: Air compressor lubricant
- Cold source: Water

Diagram showing the flow of the simple and recuperative cycles with the mentioned working fluid and sources.
Experimental setup

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Quantity</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermocouple</td>
<td>Temperature</td>
<td>0.5°C</td>
</tr>
<tr>
<td>Pressure transducer</td>
<td>Pressure</td>
<td>0.08 bar</td>
</tr>
<tr>
<td>Piezoelectric pressure transducer</td>
<td>Pressure</td>
<td>0.01 bar</td>
</tr>
<tr>
<td>Flow meter</td>
<td>Flow rate</td>
<td>4 l/min</td>
</tr>
<tr>
<td>Torque &amp; power meter</td>
<td>Torque</td>
<td>0.1 Nm</td>
</tr>
<tr>
<td></td>
<td>Angular speed</td>
<td>1 rpm</td>
</tr>
</tbody>
</table>

- Thermocouple: Cycle points thermodynamic properties
- Pressure transducer: Compressor oil flow rate, HTHX rate of heat transfer (indirect), Working fluid mass flow rate (indirect)
- Flow meter: Expander mechanical power
- Torque & power meter: Expander indicated diagram
- Piezoelectric pressure transducer: Expander indicated diagram
### Results and discussion – ORC Performance

<table>
<thead>
<tr>
<th>Cycle parameters</th>
<th>Simple cycle</th>
<th>Recuperative cycle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pump in pressure [bar]</td>
<td>3.4</td>
<td>3.76</td>
</tr>
<tr>
<td>Pump out pressure [bar]</td>
<td>10.6</td>
<td>13.0</td>
</tr>
<tr>
<td>Pump in temperature [°C]</td>
<td>19.3</td>
<td>14.6</td>
</tr>
<tr>
<td>HTHX out temperature [°C]</td>
<td>85.2</td>
<td>81.4</td>
</tr>
<tr>
<td>Pump mechanical power [kW]</td>
<td>1.10</td>
<td>0.65</td>
</tr>
<tr>
<td>Expander mechanical power [kW]</td>
<td>3.23</td>
<td>3.66</td>
</tr>
<tr>
<td>Working fluid mass flow rate [kg/s]</td>
<td>0.295</td>
<td>0.394</td>
</tr>
<tr>
<td>HTHX heat rate [kW]</td>
<td>57.25</td>
<td>60.78</td>
</tr>
<tr>
<td><strong>Net cycle power [kW]</strong></td>
<td><strong>2.13</strong></td>
<td><strong>3.01</strong></td>
</tr>
<tr>
<td><strong>Net cycle efficiency [%]</strong></td>
<td><strong>3.72</strong></td>
<td><strong>4.96</strong></td>
</tr>
</tbody>
</table>

- The system is controlled through the **pump rotational speed variation** (brushless motor), while the **expander rotational speed is constrained by grid frequency**
- **Pressure and temperature levels** are directly related to the heat source (**compressor oil 80-100°C**) and heat sink (**tap water 15-25°C**)
- Both the system operate in similar thermal input condition (alternatively coupled with the same compressor)
- Different mass flow rate (higher pressure in recuperative expander inlet cause a greater WF density)
- **Better performance for the recuperative cycle**, in terms of power production and overall cycle efficiency
Results and discussion – Indicated diagrams

- The trailing vane is taken as reference for the angular position.
- **Expander mechanical efficiency**
  - Simple 71.8%
  - Recuperative 81.5%
- **Over-expansion** occurs in the simple cycle expander, while **under-expansion** occurs in the recuperative cycle expander.
- Greater mechanical power (enclosed area in P-V diagram) for the recuperative expander.
Results and discussion – Exergy analysis

Exergy analysis

System compared to ideal cycle with finite capacity heat source

IDEAL EFFICIENCY

\[ \eta_{id} = 1 - \frac{T_0}{LMTD_{heat\ source}} \]

EXERGY EFFICIENCY

\[ \eta_{exe} = \frac{\eta}{\eta_{id}} \]

Exergy efficiency

<table>
<thead>
<tr>
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<tbody>
<tr>
<td>Simple cycle</td>
<td>19.5%</td>
</tr>
<tr>
<td>Recuperative cycle</td>
<td>23.4%</td>
</tr>
</tbody>
</table>

Exergy loss share for recuperative cycle

- LTHX: 29.7%
- HTHX: 29.3%
- EXP: 7.7%
- PUMP: 4.4%
- REC: 28.9%

Main contribution: LTHX, HTHX and expander
Conclusions

An experimental study is carried out on two ORC recovery system equipped with Sliding-Vane Rotary Expanders. They are respectively in simple and recuperative configurations and are coupled with the same thermal source: hot lubricant from a mid-size air compressor.

**Simple cycle** reaches a net power of **2.13 kW** with a cycle efficiency of **3.72%**

**Recuperative cycle** reaches a net power of **3.01 kW** with a cycle efficiency of **4.96%**

**Simple cycle expander** has a mechanical efficiency of **71.8%**

**Recuperative cycle expander** has a mechanical efficiency of **81.5%**

Exergy analysis on the **Recuperative cycle** highlights the major exergy loss contribution: LTHX, HTHX, expander.

Future works will focus on system optimization and working fluid replacement.
THANKS FOR YOUR ATTENTION

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