Numerical investigations on a Trilateral Flash Cycle under system off-design operating conditions

Matteo Marchionni\textsuperscript{a}, Giuseppe Bianchi\textsuperscript{a}, Savvas A. Tassou\textsuperscript{a}, Obadah Zaher\textsuperscript{b}, Jeremy Miller\textsuperscript{b}

\textsuperscript{a}Brunel University London, Uxbridge UB8 3PH, United Kingdom
\textsuperscript{b}Spirax Sarco Engineering PLC, GL53 8ER Cheltenham, United Kingdom

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Outline

• Overview on low grade waste heat potential

• Modelling activities on Trilateral Flash Cycle (TFC) system

• Off-design simulations

• Sensitivity analysis

• Conclusions and future work
Waste Heat Potential (WHP)

- Low thermal grade WHP in industry represents the 4% of the world final energy consumption
- Highest amount of heat rejected into the environment from the energy intensive industrial sectors
Waste Heat Potential

UK low thermal grade WHP accounts for almost 50 TWh (5.4% of the EU-28 WHP)
TFC vs ORC

<table>
<thead>
<tr>
<th>Heat recovery</th>
<th>Energy conversion</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>TFC</strong> Single phase, high 2\textsuperscript{nd} law efficiency</td>
<td>Larger density change, higher efficiency</td>
</tr>
<tr>
<td><strong>ORC</strong> Two-phase, compact heat exchangers</td>
<td>Realistic expansion ratio, safer blade environment</td>
</tr>
</tbody>
</table>
1D modelling approach

- Heat recovery loop neglected
- Hot/cold water as heating/cooling source
- Map based components
- Power quantities purely mechanical
- REFPROP for fluid thermo-physical properties
Heater and condenser

**OUTPUTS**
- Refrigerant Quality
- Heat exchangers pressure drops
- Working fluid outlet temperatures

**SWEP model**
- Several working points
- Off-design outputs

**GT-SUITE model**
- Geometrical data
- Heat exchanger material
- Off-design points

**Map**
- Best fitting coefficient of Nusselt-Reynolds based correlations

**Refrigerant mass flow rate**
**Plate Heat exchanger model**

**Temperatures of the hot/cold source**
Heat transfer correlations

- 1-D discretization
- Heat transfer correlations depending on heat exchanger and fluid phase
- Rayleigh-Plesset equation to predict vapor formation and two-phase region extension
- Heat exchanger inertia depending on material and geometrical features
Pump and expander

**PUMP**
- Input data
  - Revolution speed
  - Pressure rise
  - Power consumption

**EXPANDER**
- Intake manifold
- Expander cells
- Exhaust manifold
- Outlet pipe
  - Scalar variables
- Inlet pipe
  - Vector variables
- Heater
- Inlet boundary conditions
- Outlet boundary conditions

**Process data**
- Interpolation between 2000 and 3500 RPM
- Isentropic efficiency from power consumption

**Performance maps**
Reference conditions

<table>
<thead>
<tr>
<th>System performance</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat load [kW]</td>
<td>2001</td>
</tr>
<tr>
<td>Heat rejected [kW]</td>
<td>1917</td>
</tr>
<tr>
<td>Pump power consumption [kW]</td>
<td>23</td>
</tr>
<tr>
<td>Expanders power [kW]</td>
<td>110</td>
</tr>
<tr>
<td>Net power output [kW]</td>
<td>86</td>
</tr>
<tr>
<td>Expander efficiency [%]</td>
<td>74.0</td>
</tr>
<tr>
<td>Thermal efficiency [%]</td>
<td>4.3</td>
</tr>
</tbody>
</table>

Heat load: 2001 kW
Heat rejected: 1917 kW
Pump power consumption: 23 kW
Expanders power: 110 kW
Net power output: 86 kW
Expander efficiency: 74.0%
Thermal efficiency: 4.3%
# Off-design simulation matrix

<table>
<thead>
<tr>
<th></th>
<th>Min</th>
<th>Reference</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature heat source [°C]</td>
<td>75</td>
<td>85</td>
<td>95</td>
</tr>
<tr>
<td>mass flow rate hot source [kg/s]</td>
<td>5.84</td>
<td>7.84</td>
<td>10.19</td>
</tr>
<tr>
<td>Expanders speed [RPM]</td>
<td>3000</td>
<td>4500</td>
<td>6000</td>
</tr>
<tr>
<td>Pump speed [RPM]</td>
<td>2500</td>
<td>3000</td>
<td>3500</td>
</tr>
<tr>
<td>Control valve opening</td>
<td>9%</td>
<td>100%</td>
<td>100%</td>
</tr>
</tbody>
</table>
Expander revolution speed

- Expander efficiency considerably affected by its revolution speed
- Maximum power occurs at the optimal expander operating point (pump power fixed by the speed)
- The highest quality of the refrigerant occurs close to the optimal operating point of the expander
Pump revolution speed

- Expander performance barely affected by a change in the pump revolution speed (drop of the volumetric efficiency caused by a lower refrigerant quality is balanced by the increased mass flow rate of the working fluid due to the rise of the pump speed).

- Net power output decreases due to increased pump power consumption.

- Cycle efficiency drops due to net power output decrease and heat recovery increase.
Hot source inlet temperature

- No influence on the expander efficiency
- Greater impact on outlet quality at the heater than on the cycle pressure ratio
- Higher power output is due to a greater volume flow rate at the expander inlet
Hot source mass flow rate

Same effects than previous case but with smoother trends
Control valve opening area

- Refrigerant quality at the expander inlet, and so the power output, increase when the control valve is operated.
- No effect is shown on the expander efficiency.
- Thermal efficiency resembles the net power output trend (thermal load fixed).

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Sensitivity analysis

- The expander revolution speed and the hot source inlet temperature present a more pronounced effect on the system power output.

- Pump revolution speed and control valve opening affect deeply the refrigerant quality at the expander inlet.
Conclusions

• The closing of the control valve increases the refrigerant quality at the expander inlet and consequently the power output of the machine

• The expander revolution speed should be varied in a narrow range close to its optimal operating condition

• The hot source inlet conditions affect deeply the net power output of the system due to a higher refrigerant quality at the expander inlet rather than an increased expansion ratio across the machine
Future work

• Coupling of the pump and expander with electric machine

• Friction modelling in the twin screw expander

• Experimental validation of the model implemented through an industrial scale prototype unit

• Development of a control system to regulate and optimize the refrigerant quality at the expander inlet
Acknowledgements

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