Dynamic analysis of off-grid ORC plants with various solutions for the thermal storage

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Outline

- Introduction
- ORC system description
- Model definition
- Case study w/o thermal storage
- Case study w/ thermal storage
- Conclusions
Introduction

Off-grid application of biomass boiler & ORC system

▲ Good performance at partial load
▲ Low Operation&Maintenance requirements
▲ High flexibility
► Use of thermal storage solutions for real time coupling with electric power demand
ORC system description

Nominal operating conditions

<table>
<thead>
<tr>
<th>Parameters</th>
<th>units</th>
<th>values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boiler thermal power</td>
<td>kW</td>
<td>5141</td>
</tr>
<tr>
<td>ORC electrical power</td>
<td>kW</td>
<td>1043</td>
</tr>
<tr>
<td>ORC efficiency</td>
<td>%</td>
<td>20.2</td>
</tr>
<tr>
<td>(T_{OUT,ORC} = T_{IN,Boiler})</td>
<td>°C</td>
<td>240</td>
</tr>
<tr>
<td>(T_{OUT,Boiler} = T_{IN,ORC})</td>
<td>°C</td>
<td>300</td>
</tr>
</tbody>
</table>

Partial load performance

@ \(T_{IN,ORC} = 300°C\)

@ \(\dot{m}_{oil} = 34.8\) kg/s
**ORC system description**

### Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Piping ID/th</td>
<td>mm</td>
<td>80 / 7</td>
</tr>
<tr>
<td>Oil mass</td>
<td>kg</td>
<td>1000</td>
</tr>
<tr>
<td>( \rho_{\text{oil}} )</td>
<td>kg/m(^3)</td>
<td>840</td>
</tr>
<tr>
<td>Equivalent length</td>
<td>m</td>
<td>240</td>
</tr>
<tr>
<td>Overall oil mass flow</td>
<td>kg/s</td>
<td>38.4</td>
</tr>
<tr>
<td>Oil velocity</td>
<td>m/s</td>
<td>8.2</td>
</tr>
</tbody>
</table>

One-dimensional finite difference methods for solving differential equations with spatial resolution of 0.5 m (480 nodes)

\[
\rho_{\text{oil}} c_{p,\text{oil}} \frac{\partial T_{\text{oil}}(x)}{\partial t} = -u_{\text{oil}} \rho_{\text{oil}} c_{p,\text{oil}} \frac{\partial T_{\text{oil}}(x)}{\partial x} + \frac{4U}{D_{\text{int}}} [T_{\text{steel}}(x) - T_{\text{oil}}(x)]
\]

\[
\rho_{\text{steel}} c_{p,\text{steel}} \frac{\partial T_{\text{steel}}(x)}{\partial t} = k_{\text{oil}} \frac{\partial^2 T_{\text{oil}}(x)}{\partial x^2} + \frac{U}{t} [T_{\text{oil}}(x) - T_{\text{steel}}(x)] + \frac{\dot{Q}}{\pi D_{\text{int}} t L}
\]

Boundary conditions

\[
\begin{align*}
T_{\text{oil}, x=0} &= T_{\text{in}, \text{Boiler}} \\
\frac{\partial T_{\text{steel}, x=0}}{\partial x} &= 0 \\
\frac{\partial T_{\text{steel}, x=L}}{\partial x} &= 0
\end{align*}
\]

\[
\text{Nu} = 0.023 \text{Re}^{0.8} \text{Pr}^n
\]

**Dittus-Boelter**

Forced convection for turbulent flow

Uniform thermal power distribution generated by the biomass combustion
ORC system description

Supply & Return Piping

<table>
<thead>
<tr>
<th>Parameters</th>
<th>units</th>
<th>values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Piping ID/th</td>
<td>mm</td>
<td>150 / 10</td>
</tr>
<tr>
<td>Oil mass</td>
<td>kg</td>
<td>1000</td>
</tr>
<tr>
<td>$\rho_{oil}$</td>
<td>kg/m$^3$</td>
<td>840</td>
</tr>
<tr>
<td>Length</td>
<td>m</td>
<td>50</td>
</tr>
<tr>
<td>Oil velocity</td>
<td>m/s</td>
<td>2.3</td>
</tr>
</tbody>
</table>

One-dimensional finite difference methods for solving differential equations with spatial resolution of 0.5 m (100 nodes)

\[
\begin{align*}
\rho_{oil}c_{oil} \frac{\partial T_{oil}(x)}{\partial t} &= -u_{oil}\rho_{oil}c_{oil} \frac{\partial T_{oil}(x)}{\partial x} + \frac{4U}{D_{int}} \left[ T_{steel}(x) - T_{oil}(x) \right] \\
\rho_{steel}c_{steel} \frac{\partial T_{steel}(x)}{\partial t} &= k_{oil} \frac{\partial^2 T_{oil}(x)}{\partial x^2} + \frac{U}{t} \left[ T_{oil}(x) - T_{steel}(x) \right] + \frac{\dot{Q}}{\pi D_{int} t_L}
\end{align*}
\]

Boundary conditions:

\[
\begin{align*}
T_{oil,x=0} &= T_{in,Boiler} \\
\frac{\partial T_{steel,x=0}}{\partial x} &= 0 \\
\frac{\partial T_{steel,x=L}}{\partial x} &= 0
\end{align*}
\]

No heat generation source

Nu = 0.023Re$^{0.8}$Pr$^n$

Dittus-Boelter

Forced convection for turbolent flow
ORC system description

Case study

<table>
<thead>
<tr>
<th>Time (s)</th>
<th>Interval (s)</th>
<th>Event</th>
<th>Control</th>
</tr>
</thead>
<tbody>
<tr>
<td>t = 0</td>
<td></td>
<td>Electrical Load</td>
<td>Boiler power 30%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.2 MW</td>
<td>ORC power 24%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>ORC oil flow 5.0 kg/s</td>
<td></td>
</tr>
<tr>
<td>t = 50</td>
<td>900</td>
<td>Electrical Load ↑</td>
<td>ORC power 100%</td>
</tr>
<tr>
<td>Stepwise</td>
<td>(15 min)</td>
<td>1 MW</td>
<td>Boiler power ↑</td>
</tr>
<tr>
<td></td>
<td></td>
<td>ORC oil flow 34.8 kg/s</td>
<td></td>
</tr>
<tr>
<td>t = 950</td>
<td>1000</td>
<td>Nominal conditions</td>
<td>ORC power 100%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Boiler power 100%</td>
</tr>
</tbody>
</table>

H_p: ORC response assumed instantaneous
Boiler ramp of 15 min from 30% to 100%
Case study without thermal storage

Overview of the system:

- **BOILER**:
  - 300 °C, 34.8 kg/s
  - 282 °C, 34.8 kg/s
  - 300 °C, 29.8 kg/s
  - 166 °C, 5.0 kg/s

- **ORC**:
  - 300 °C, 34.8 kg/s

- **BY-PASS**

Load scenarios:

- **0 S**: Load 0.2 MW, BOILER 30%
- **50 S**: Load 1 MW, BOILER↑
- **950 S**: Load 1 MW, BOILER 100%

Graphs showing temperature changes over time for various components:

- **T_{out,BOILER}**
- **T_{in,ORC}**
- **T_{in,BOILER}**
- **T_{out,ORC}**

Graph indicating ORC El. Power & Boiler Th. Power over time:

- **Green** (Boiler)
- **Red** (ORC)

Graph time scale: 0 to 1500 seconds.
Case study without thermal storage

- ORC min power < 100% even with longer pipes
- Solution: Introduction of thermal storage

34.8 kg/s

0 S
Load 0.2 MW
Boiler 30%

50 S
Load 1 MW
Boiler↑

950 S
Load 1 MW
Boiler 100%

ORC Minimum Electric Power, %

Supply & Return Pipes length, m
Thermal energy storage (TES)

- Solid sensible heat storage for limiting ORC electric power undershoot
- One block of storage material crossed by carbon steel pipes
- Optimization of parameter TH (thickness) as distance between pipes

Storage design and weight defined by TH and storage material

<table>
<thead>
<tr>
<th>Parameters</th>
<th>units</th>
<th>values</th>
</tr>
</thead>
<tbody>
<tr>
<td>N pipes</td>
<td></td>
<td>36</td>
</tr>
<tr>
<td>Pipes length</td>
<td>m</td>
<td>50</td>
</tr>
<tr>
<td>Oil velocity</td>
<td>m/s</td>
<td>2.3</td>
</tr>
<tr>
<td>TH</td>
<td>mm</td>
<td>0 ÷ 50</td>
</tr>
</tbody>
</table>

(a) Concrete / 300 °C / after boiler
(b) Cast iron / 300 °C / after boiler
(c) Concrete / 370 °C / after boiler
(d) Cast iron / 370 °C / after boiler
(e) Concrete / 370 °C / before boiler
(f) Cast iron / 370 °C / before boiler

Two dimensional finite difference method with cylindrical coordinates monitoring temperature distribution on both radial and axial direction.
Results with thermal storage

Cases (a,b): T=300°C / after boiler

- Cast Iron (50 W/mK)
- Concrete (2.2 W/mK)

**BOILER**

34.8 kg/s

**TH. ST.**

**BY-PASS**

**ORC**

**CAST IRON**

Text storage \((r_{ext})\)

Tav storage

Tsteel pipe

T oil

Storage length, m

Temperatures:

- 292 °C

**CONCRETE**

Text storage \((r_{ext})\)

Tav storage

Tsteel pipe

T oil

Storage length, m

Temperatures:

- 268 °C

**G. Di Marcoberardino, 4th Int. Seminar ORC Systems, Milan, 13th September 2017**
Results with thermal storage

Cases (c,d): T=370°C / after boiler

<table>
<thead>
<tr>
<th>Time (s)</th>
<th>Control</th>
</tr>
</thead>
<tbody>
<tr>
<td>t = 0</td>
<td>m1 = 34.8 kg/s</td>
</tr>
<tr>
<td></td>
<td>m3 = 5.0 kg/s (ORC 24%)</td>
</tr>
<tr>
<td>t = 50</td>
<td>m1 = m3 = 34.8 kg/s</td>
</tr>
<tr>
<td></td>
<td>Stepwise ORC 100%</td>
</tr>
</tbody>
</table>

Example Concrete TH=12mm
Results with thermal storage

Cases \((e,f)\): \(T=370°C\) / before boiler

<table>
<thead>
<tr>
<th>Time (s)</th>
<th>Control</th>
</tr>
</thead>
<tbody>
<tr>
<td>(t = 0)</td>
<td>(m1 = 34.8) kg/s</td>
</tr>
<tr>
<td>(m3 = 5.0) kg/s (ORC 24%)</td>
<td></td>
</tr>
<tr>
<td>(t = 50)</td>
<td>(m1 = m3 = 34.8) kg/s</td>
</tr>
</tbody>
</table>

Stepwise ORC 100%

Example Cast Iron \(TH=8mm\)
Results with thermal storage

▲ Cases with max T 370°C allows ORC to operate at 100% with TH > 15 mm
  ❖ Cast Iron \((d,f)\) has better performance than concrete due to its higher thermal conductivity (50 vs 2.2 W/mK)
  ❖ Cast Iron density penalizes storage weight 19 tons \((f)\) VS 11 tons \((e)\)
▲ Storage before boiler implies potentially higher heat flux to oil due to lower temperatures

(a)Concrete / 300 °C / after boiler
(b)Cast iron / 300 °C / after boiler
(c)Concrete / 370 °C / after boiler
(d)Cast iron / 370 °C / after boiler
(e)Concrete / 370 °C / before boiler
(f) Cast iron / 370 °C / before boiler
Results with thermal storage

▲ Higher performance of cast iron highlighted with boiler ramp of 45 min
   ❖ Use of concrete (c,e) penalizes ORC power production

- (c) Concrete / 370 °C / after boiler
- (d) Cast iron / 370 °C / after boiler
- (e) Concrete / 370 °C / before boiler
- (f) Cast iron / 370 °C / before boiler
Conclusions

► A dynamic model of an off-grid system based on 1 MWel Turboden biomass ORC plant was developed in Aspen Custom Modeler

► Thermal storage solutions composed by a bunch of pipes employing either concrete or cast iron as coating materials were considered

► System without storage shows a poor capacity to comply with load variations (Min power ~50%, Transient of 1200 s)

► Adoption of a diathermic oil storage with maximum temperature of 370°C can maintain ORC system at the required electrical power

► Despite greater weight (19 vs 11 tons), cast iron has better performance than concrete due to higher thermal conductivity (50 vs. 2.2 W/mK)

► Techno/economic optimization of storage temperature and design will be investigated in the future
Thank you for your attention!

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