Towards model-based control of a steam Rankine process for engine waste heat recovery

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Context

- 30% of the energy produced by internal combustion engine (ICE) is released as heat through exhaust gases
  - partial recovery is possible via systems implementing the thermodynamic Rankine cycle

- Intensive research dedicated to design issues
  - comparatively little research on control issues

- Control of “mobile” Rankine systems is difficult, due to
  - multivariable and coupled nature of the process
  - fast transients
  - safe operating range of components
Objective and workplan

- Developing a control system to be implemented on a test bench hosting a pilot Rankine system

**Steps**

- Developing a simulator for control prototyping
- Control design
  - Supervisory layer to manage start-up and shut-down modes
  - Preliminary control strategy for power-production mode
- Control validation on data coming from a motorway driving cycle
- ...

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System layout

- Pilot Rankine steam process for recovering waste heat from the exhaust gas of a spark-ignition (SI) engine

### System layout

**Via an evaporator, exhaust gas supplies heat to water circulating in a closed loop**

1. **Evaporator**
   - Steam expansion produces mechanical power (and electricity via a generator)
   - Steam is converted into liquid in a condenser

2. **Condenser**
   - A pump circulates water at the required pressure

3. **Pump**
   - By-passes added for safety and flexibility

4. **Evaporator by-pass**

**System description**

- **Engine exhaust line**
- **Evaporator**
- **Pump**
- **Condenser**
- **Exchanger**
- **Expander**

**Technical details**

- **$V_{O_{evap}}^{SP}$**
- **$V_{O_{exp}}^{SP}$**
- **$N_{pump}^{SP}$**
- **$m_{pump}^{SP}$**
- **$N_{exp}^{SP}$**
Modeling of heat-exchangers: moving-boundary principle

- 3 volumes: liquid – two-phase – vapor

- Assumptions:
  - uniform pressure
  - negligible thermal conduction along the wall

- Equations derived from mass and energy balances
Modeling: evaporator (1)

**Working fluid mass balance:**

\[
\frac{dm_i(t)}{dt} = \dot{m}_{in,i}(t) - \dot{m}_{out,i}(t)
\]

**Mass expression:**

\[
m_i(t) = \rho_i(p(t), h_i(t)) \ V_f \ L_i(t)
\]

**yields to:**

\[
\left( \frac{\partial \rho}{\partial p} \bigg|_{h_i} \frac{dp}{dt} + \frac{\partial \rho}{\partial h_i} \bigg|_p \frac{dh_i}{dt} \right) \ V_f \ L_i(t) + \rho_i(p(t), h_i(t)) \ V_f \ \frac{dL_i}{dt} = \dot{m}_{in,i}(t) - \dot{m}_{out,i}(t)
\]
Modeling : evaporator (2)

- **Working fluid energy balance:**

\[
\rho_i(p(t), h_i(t)) V_f L_i(t) \frac{dh_i}{dt} =
\dot{m}_{in,i}(t) \left( h_{in,i}(t) - h_i(t) \right) - \dot{m}_{out,i}(t) \left( h_{out,i}(t) - h_i(t) \right) + \dot{Q}_{f,i}(t) + \frac{dp}{dt} V_f L_i(t)
\]

where

\[
\dot{Q}_{f,i}(t) = V_f \alpha_f \left( T_{w,i}(t) - T_{f,i}(p(t), h_i(t)) \right) L_i(t)
\]

- **Wall energy balance:**

\[
m_w c_p \frac{dT_{w,i}}{dt} L_i(t) = \dot{Q}_{exh,i}(t) - \dot{Q}_{f,i}(t)
\]

\[
\dot{Q}_{exh,i}(t) = \dot{m}_{exh}(t) c_{pexh} \left( 1 - \exp\left(-\frac{\alpha_{exh} S_{exh}}{\dot{m}_{exh}(t) c_{pexh}}\right) \right) (T_{exh}(t) - T_w(t)) L_i(t)
\]
Modeling: evaporator – expander DAE

- Differential algebraic equations (DAE) system:
  - evaporator balances with interface equations
  - expander static model
  \[ \dot{m}_{exp} = N_{exp} \rho \eta_{exp} \]
  - result in a DAE with 7 dynamic states

- Fast / slow modes analysis:
  - slow (wall inertia) \( T_{w1}, T_{w2}, T_{w3} \)
  - middle (liquid inertia) \( L_1 \)
  - fast (pressure, vapor and two-phase) \( p, L_2, h_{out} \)
Model reduction

- Fast / slow modes separation:
  - fast dynamic states approximated by static variables
  - result in 3rd or 4th order model

- 3rd order model equations:

\[
\begin{align*}
    m_w c_w \frac{dT_{w,i}}{dt} &= \dot{Q}_{exh,i} - \dot{Q}_{f,i}, \quad i = 1, 2, 3 \\
    0 &= -0.5 V_f \rho_1 L_1 \dot{h}_{in} + m_{in,1}(h_{in,1} - h_l) + \dot{Q}_{f,1} L_1 \\
    0 &= m_{in,1}(h_l - h_v) + \dot{Q}_{f,2} L_2 \\
    0 &= m_{in,1}(h_v - h_{out,3}) + \dot{Q}_{f,3}(1 - L_1 - L_2)
\end{align*}
\]
Model reduction: validation

- Open-loop comparison:

![Graph showing model reduction validation](image)

- Zoom on the graph for better visualization.
Control: decentralized PI

- **Identification**

- **Limits of decentralized PI control**

<table>
<thead>
<tr>
<th>“Hot” operating point</th>
<th>“Cold” operating point</th>
</tr>
</thead>
<tbody>
<tr>
<td>$y_0$</td>
<td>$y_0$</td>
</tr>
<tr>
<td>$SH$</td>
<td>$SH$</td>
</tr>
<tr>
<td>$p$</td>
<td>$p$</td>
</tr>
<tr>
<td>200 K</td>
<td>200 K</td>
</tr>
<tr>
<td>2.5 MPa</td>
<td>2.5 MPa</td>
</tr>
<tr>
<td>$u_0^0$</td>
<td>$u_1^0$</td>
</tr>
<tr>
<td>$m_{pump}$</td>
<td>$m_{pump}$</td>
</tr>
<tr>
<td>$N_{exp}$</td>
<td>$N_{exp}$</td>
</tr>
<tr>
<td>0.005855 kg/s</td>
<td>0.0010156 kg/s</td>
</tr>
<tr>
<td>712.5 rpm</td>
<td>134.3 rpm</td>
</tr>
<tr>
<td>$d_0^0$</td>
<td>$d_1^0$</td>
</tr>
<tr>
<td>$T_{exh}$</td>
<td>$T_{exh}$</td>
</tr>
<tr>
<td>$m_{exh}$</td>
<td>$m_{exh}$</td>
</tr>
<tr>
<td>$T_{in}$</td>
<td>$T_{in}$</td>
</tr>
<tr>
<td>600°C</td>
<td>400°C</td>
</tr>
<tr>
<td>0.05 kg/s</td>
<td>0.02 kg/s</td>
</tr>
<tr>
<td>70°C</td>
<td>30°C</td>
</tr>
</tbody>
</table>

**TABLE I**

**TABLE II**

<table>
<thead>
<tr>
<th>“Hot” operating point</th>
<th>“Cold” operating point</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_p$</td>
<td>$K_p$</td>
</tr>
<tr>
<td>$\tau_p$</td>
<td>$\tau_p$</td>
</tr>
<tr>
<td>$T_p$</td>
<td>$T_p$</td>
</tr>
<tr>
<td>$-1.36e^2$ K/kg.s</td>
<td>$-4.28e^5$ K/kg.s</td>
</tr>
<tr>
<td>60.1 s</td>
<td>345 s</td>
</tr>
<tr>
<td>8.4 s</td>
<td>30 s</td>
</tr>
</tbody>
</table>

**TABLE II**

Identified model parameters around the two operating points
Control: nonlinear inversion-based

- Decentralized feedback controller
  - with inverse of reduced model in the feedforward path:

\[ \text{Controller} \]

\[ y^{sp} \rightarrow \text{Inverse reduced model} \rightarrow u_d \rightarrow \text{Decentralized feedback controller} \rightarrow u \rightarrow \text{Rankine system} \rightarrow d \rightarrow y \]

- External conditions

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Control: nonlinear inversion equations

- **Dynamic (wall):**

  \[
  \frac{dT_{w,i}}{dt} = \frac{\dot{Q}_{\text{exh},i} - \dot{Q}_{f,i}}{m_w c_w}, \quad i = 1, 2, 3
  \]

- **Pump mass flow:**

  \[
  u_{1,d} = \frac{(T_3 - T_{w3}) S_R \alpha_3}{h_v - h_{out} + \frac{(T_3 - T_{w3})(h_l - h_{in}) \alpha_3}{\alpha_1 (T_{w1} - T_1)} + \frac{(T_3 - T_{w3})(h_v - h_l) \alpha_3}{\alpha_2 (T_{w2} - T_2)}}
  \]

- **Expander speed:**

  \[
  u_{2,d} = \frac{u_{1,d}}{\rho_{out,3} \eta_{exp} V_{exp}}
  \]
Control: co-simulation

- The resulting order is reasonably low: “only” 19 dynamical states
Control: co-simulation
Simulation results with real data from a Renault Scenic with a 2L-F4RT engine

- Exhaust gas conditions:

![Graph showing exhaust gas conditions](image)

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Simulation results with real data from a Renault Scenic with a 2L-F4RT engine

- **Pressure and temperature control:**

![Graphs showing pressure and superheating control with real data from a Renault Scenic with a 2L-F4RT engine.](image)

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Perspectives

- **Pursuing validation**
  - in simulation on broader range of driving profiles
  - on the experimental test bench

- **Improving the control strategy**
  - expander speed saturations
  - optimal set points