Modeling and control of Rankine based waste heat recovery systems for heavy duty trucks

Vincent GRELET\textsuperscript{1,2,3}, Thomas REICHE\textsuperscript{1}, Madiha NADRI\textsuperscript{2}, Pascal DUFOUR\textsuperscript{2} and Vincent LEMORT \textsuperscript{3}

\textsuperscript{1}Volvo Group Trucks Technology Advanced Technology and Research, 1 avenue Henri Germain, 69800 Saint Priest, France
\textsuperscript{2}Université de Lyon, Lyon F-69003, Université Lyon 1, CNRS UMR 5007, Laboratory of Process Control and Chemical Engineering (LAGEP), Villeurbanne 69100, France
\textsuperscript{3}LABOTHAP, University of Liege, Campus du Sart Tilman Bat. B49 B4000 Liege, Belgium

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Context and motivations

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Waste heat recovery based on the Rankine cycle is a promising technique to increase fuel efficiency.

Long and frequent transient behavior of the heat sources makes good control strategies mandatory.
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Waste heat recovery Rankine cycle based

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- It is then pre-heat, vaporize and superheat ($2 \to 3$).
- It expands from evaporating to condensing pressure ($3 \to 4$).
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- The liquid is compressed from condensing to evaporating pressure (1 → 2).
- It is then pre-heat, vaporize and superheat (2 → 3).
- It expands from evaporating to condensing pressure (3 → 4).
- It condenses and goes back to liquid state (4 → 1).
Studied system

- Waste heat recovery Rankine cycle based
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Model assumptions and governing equations

Model assumptions

- Geometry is reduced to a single pipe in pipe HEX.
- Secondary (or transfer) fluid always in single phase.
- Conduction is neglected.
- Pressure drops are neglected.
- Pressure dynamic is neglected.
- Fluid properties are evaluated at the outlet of each node.
- Mass flow rates are supposed constant along the HEX.

Governing equation

- **Internal fluid**
  \[
  A_{cross,f} \frac{\partial \rho_f h_f}{\partial t} + \frac{\partial \dot{m}_f h_f}{\partial z} + \dot{q}_{f,int} = 0. \tag{1}
  \]

- **Internal pipe wall**
  \[
  \dot{q}_{f,int} + \dot{q}_{g,int} = \frac{\partial m_{w,int} c_{p,w,int} T_{w,int}}{\partial t}. \tag{2}
  \]

- **External fluid**
  \[
  \frac{\partial \dot{m}_g c_{p,g} T_g}{\partial z} + \frac{\partial \dot{m}_g c_{p,g} T_g}{\partial t} + \dot{q}_{g,int} + \dot{q}_{g,ext} = 0. \tag{3}
  \]

- **External pipe wall**
  \[
  \dot{q}_{g,ext} + \dot{q}_{amb,ext} = \frac{\partial m_{w,ext} c_{p,w,ext} T_{w,ext}}{\partial t}. \tag{4}
  \]
Heat transfer

Heat transfer coefficients

\[
\begin{align*}
\alpha_g &= \alpha_{\text{ref}, g} \dot{m}_g^n \\
\alpha_{f, \text{liq}} &= \alpha_{\text{ref}, f, \text{liq}} \dot{m}_{f}^{n_f, \text{liq}} \\
\alpha_{f, 2\varphi} &= \alpha_{f, \text{liq}} \ldots \\
&\quad \ldots \left\{ \left(1 - q\right)^{0.01} \left[ \left(1 - q\right) + 1.2q^{0.4} \frac{\rho_{f, \text{sat}, \text{liq}}}{\rho_{f, \text{sat}, \text{vap}}} \right]^{0.37} \right\}^{-2.2} + \ldots \\
&\quad \ldots q^{0.01} \left[ \frac{\alpha_{f, \text{vap}}}{\alpha_{f, \text{liq}}} \left(1 + 8 \left(1 - q\right)^{0.7} \frac{\rho_{f, \text{sat}, \text{liq}}}{\rho_{f, \text{sat}, \text{vap}}} \right)^{0.67} \right]^{-2} \right\}^{-0.5} \\
\alpha_{f, \text{vap}} &= \alpha_{\text{ref}, f, \text{vap}} \dot{m}_f^{n_f, \text{vap}}
\end{align*}
\]
Heat transfer

Heat transfer EGR boiler

Heat transfer exhaust boiler
Working fluid properties models

- **Temperature:**
  \[
  T_f = \begin{cases} 
  a_{T, liq} h_f^2 + b_{T, liq} h_f + c_{T, liq} & \text{if } h_f \leq h_{sat, liq} \\
  T_{sat, liq} + q (T_{sat, vap} - T_{sat, liq}) & \text{if } h_{sat, liq} \geq h_f \leq h_{sat, vap} \\
  a_{T, vap} h_f^2 + b_{T, vap} h_f + c_{T, vap} & \text{if } h_f \geq h_{sat, vap}
  \end{cases}
  \]  
\[ (9) \]

- **Density**
  \[
  \rho_f = \begin{cases} 
  a_{\rho, liq} h_f^2 + b_{\rho, liq} h_f + c_{\rho, liq} & \text{if } h_f \leq h_{sat, liq} \\
  \frac{1}{a_{\rho, 2\varphi} h_f + b_{\rho, 2\varphi}} & \text{if } h_{sat, liq} \geq h_f \leq h_{sat, vap} \\
  a_{\rho, vap} h_f^2 + b_{\rho, vap} h_f + c_{\rho, vap} & \text{if } h_f \geq h_{sat, vap}
  \end{cases}
  \]  
\[ (10) \]
Working fluid properties

**Temperature model validation**

![Temperature model validation graph](image)

**Density model validation**

![Density model validation graph](image)
The continuous set of equation (1,2,3,4) is discretized with respect to space based finite differences.

A finite volume approach is chosen where the HEX is split into \( n \) longitudinal cell.

The vector \( u \) contains the manipulated variable \( \dot{m}_{f,0} \) and the input disturbances: \( \dot{m}_{g,L}, T_{g,L}, h_{f,0}, P_{f,0} \).
The system of equations defining the response of the $i^{th}$ cell of the discretized model is:

\[
\dot{x}_i = f_i(x_i, u),
\]

where:

\[
u = [\dot{m}_{f,0}, P_{f,0}, h_{f,0}, \dot{m}_g, L, T_g, L],
\]

\[
x_i = [h_{f,i}, T_{w,\text{int},i}, T_{g,i}, T_{w,\text{ext},i}],
\]

\[
f_i(x_i, u) = \begin{bmatrix}
\frac{\dot{m}_f (h_{f,i-1} - h_{f,i}) - \alpha_{f,i} A_{\text{exch},f,\text{int}} (T_{f,i} - T_{w,\text{int},i})}{\rho_{f,i} V_f} \\
\frac{\alpha_{f,i} A_{\text{exch},f,\text{int}} (T_{f,i} - T_{w,\text{int},i}) + \alpha_g A_{\text{exch},g,\text{int}} (T_{g,i} - T_{w,\text{int},i})}{\rho_{w,\text{int}} V_{w,\text{int}}} \\
\frac{\dot{m}_g c_{pg} (T_{g,i-1} - T_{g,i}) - \alpha_g [A_{\text{exch},g,\text{int}} (T_{g,i} - T_{w,\text{int},i}) - A_{\text{exch},g,\text{ext}} (T_{g,i} - T_{w,\text{ext},i})]}{\rho_{g,i} V_{g,\text{int}}} \\
\frac{\alpha_{\text{amb}} A_{\text{exch},\text{amb,ext}} (T_{\text{amb}} - T_{w,\text{ext},i}) + \alpha_g A_{\text{exch},g,\text{ext}} (T_{g,i} - T_{w,\text{ext},i})}{\rho_{w,\text{ext}} V_{w,\text{ext}}}
\end{bmatrix}
\]

(11)
Implementation constraint

Classical automotive electronic control unit (ECU) constrains the implementation of controllers:

- Simulink based environment.
- Controller must be discretized in time.
- Backward Euler integration scheme has to be used with a sample time of 20ms.
- Calculation must stay as simple as possible (problems have to be rescaled to avoid the use of high computational capacity demand functions).
Model identification

- First order plus time delay models are identified in open loop around several operating points with output error minimization algorithm.

- The dynamic relation between the working fluid temperature and mass flow variations is:
  \[
  \Delta T_{f,L} \frac{\Delta m_f}{G} = \frac{e^{-Ds}}{1 + \tau s}.
  \]  \(\text{(15)}\)

- According to the non linearity of model 11 FOPTD parameters vary a lot.

\[
\Delta T_{f,L} \frac{\Delta m_f}{G} = \frac{e^{-Ds}}{1 + \tau s}.
\]
State of the art PID controller

- State of the art controller in the automotive industry is the PID controller.
- A well known improvement is the gain scheduling approach.
  - Gains are calculated offline and linearly interpolated according to the mass flow sensor signal.
- Several PID tuning methods have been compared on a load step change.
Nonlinear model inversion

- Fastest dynamics (i.e. fluid and gas) are canceled.
- Single phases working fluid heat transfer coefficients are assumed constant.
- The system of equations defining the response of the i\textsuperscript{th} cell can be written:

\[
\begin{align*}
0 &= \dot{m}_f (h_{f_{i-1}} - h_{f_i}) + \dot{Q}_{f_{int_i}} \\
\frac{\partial T_{w_{int_i}}}{\partial t} &= \dot{Q}_{f_{int_i}} + \dot{Q}_{g_{int_i}} \\
0 &= \dot{m}_g c_p g (T_{g_{i-1}} - T_{g_i}) + \dot{Q}_{g_{int_i}} + \dot{Q}_{g_{ext_i}} \\
\frac{\partial T_{w_{ext_i}}}{\partial t} &= \dot{Q}_{g_{ext_i}} + \dot{Q}_{amb_{ext_i}}.
\end{align*}
\] (16)

- The expression of the feedforward term $U_{\text{feedforward}}$ is then straightforward:

\[
U_{\text{feedforward}} = \frac{\sum_{i=1}^{N} \dot{Q}_{f_{int_i}}}{h_{f_0} - h_{f_L}}. \tag{17}
\]
Controllers structure

Feedback controller

Set Point

PID

U_{feedback}

External Conditions

Rankine System

outputs
Controllers structure

Nonlinear controller

- Set Point
- Inverse HEX Model
- PID
- U_{feedforward}
- U_{feedback}
- U
- Rankine System
- External Conditions
- Disturbances
- Outputs

Implementation constraint
Model identification
State of the art PID controller
Nonlinear model inversion
Controllers structure

Grelet et al., ADCHEM 2015 paper 098
Pump and expansion machine models are added to represent the high pressure part of the Rankine system.

- **Pump model:**
  \[
  \dot{m}_f = \rho_{f,\text{in}} \frac{N_{\text{pump}}}{60} C_{\text{cpump}} \eta_{\text{vol,pump}}. \tag{18}
  \]

- **Expansion machine:**
  \[
  \dot{m}_f = k_{\text{eq}} \sqrt{\rho_{f,\text{in}} P_{f,\text{in}} \left(1 - \frac{P_{f,\text{in}}}{P_{f,\text{out}}}\right)^{-2}}. \tag{19}
  \]
Controller comparison

- Initial set point and disturbances change are not handled by PID controller.
- The non-linear controller reduces the deviation from +/-10°C with the PID to +/-3°C.
Conclusion

- A control strategy for temperature management of WHRS Rankine cycle based is presented.
- Main objective to stabilize the temperature around a given set point is better achieved by using a non linear controller.
- Non linear controller is compliant with implementation constraint relative to automotive industry.

Next steps

- Controller sensitivity to parameters mismatch.
- Controller robustness.
- Optimal high level control strategy (set points generation).
Contacts and discussion

Authors

- Vincent GRELET: vincent.grelet@volvo.com
- Thomas REICHE: thomas.reiche@volvo.com
- Madiha NADRI: nadri@lagep.univ-lyon1.fr
- Pascal DUFOUR: dufour@lagep.univ-lyon1.fr
- Vincent LEMORT: vincent.lemort@ulg.ac.be

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