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MODEL BASED CONTROL FOR WASTE HEAT RECOVERY HEAT EXCHANGERS RANKINE CYCLE SYSTEM IN HEAVY DUTY TRUCKS

Vincent GRELET^{1,2,3}, Pascal DUFOUR³, Madiha NADRI³, Vincent
LEMORT² and Thomas REICHE¹

¹Volvo Group Trucks Technology Advanced Technology and Research, 1 avenue Henri Germain, 69800 Saint Priest, France

²LABOTHAP, University of Liege, Campus du Sart Tilman Bat. B49 B4000 Liege, Belgium


³Université de Lyon, Lyon F-69003, Université Lyon 1, CNRS UMR 5007, Laboratory of Process Control and Chemical Engineering (LAGEP), Villeurbanne 69100, France

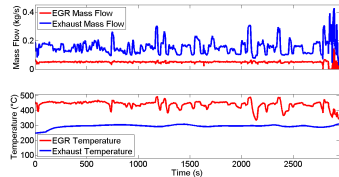
3rd International Seminar on ORC Power Systems
12-14 October, Brussels, Belgium

Table of contents

- 1 Context and motivations
- 2 Nonlinear evaporator detailed model
- 3 Controller development
 - Objective
 - Identification
 - Piecewise linear approach
 - Nonlinear model inversion
- 4 Performance evaluation
 - Methodology
 - Tracking error
 - Manipulated variable
 - IAE
- 5 Conclusion and next steps
 - Implemented controller
 - Controller performance
 - Experimental results

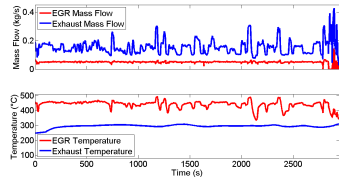
Context and motivations

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



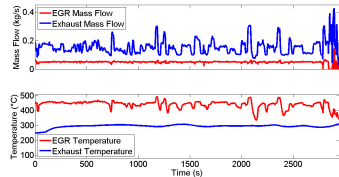
Context and motivations

- Waste heat recovery based on the Rankine cycle is a promising technique to increase fuel efficiency.
- Long and frequent transient of the heat sources make the control problem complex.



Context and motivations

- Waste heat recovery based on the Rankine cycle is a promising technique to increase fuel efficiency.
- Long and frequent transient of the heat sources make the control problem complex.
- Implementation constraints inherent to the automotive industry reduced the possibility in terms of advanced control strategies.



Detailed model (companion paper)

Model representation

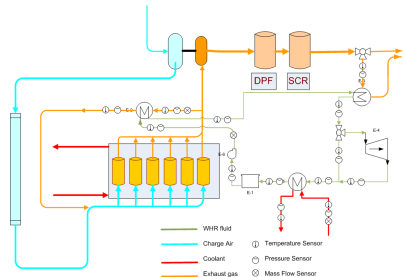
$$Z \dot{x}_i = f_i(x_i, u), \quad (1)$$

$$Z = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} \quad \begin{array}{l} u^T = \\ x_i^T = \end{array} \begin{bmatrix} \dot{m}_{f_0} & P_{f_0} & h_{f_0} & \dot{m}_{g_L} & T_{g_L} \\ \dot{m}_{f_i} & h_{f_i} & T_{w_{int_i}} & T_{g_i} & T_{w_{ext_i}} \end{bmatrix}$$

$$f_i(x_i, u) = \begin{bmatrix} \frac{\dot{m}_{f_{i-1}} \frac{h_{f_{i-1}}}{\rho_{f_{i-1}}} \frac{\partial \rho_{f_{i-1}}}{\partial h_{f_{i-1}}} + \frac{1}{\rho_{f_{i-1}}} \frac{\partial \rho_{f_{i-1}}}{\partial h_{f_{i-1}}} \alpha_{f_i} A_{exch_{int_f}} (T_{f_i} - T_{w_{int_i}})}{1 - \frac{h_{f_i}}{\rho_{f_i}} \frac{\partial \rho_{f_i}}{\partial h_{f_i}}} - \dot{m}_{f_i} \\ \frac{(\dot{m}_{f_{i-1}} h_{f_{i-1}} - \dot{m}_{f_i} h_{f_i}) - \alpha_{f_i} A_{exch_{int_f}} (T_{f_i} - T_{w_{int_i}})}{\rho_{f_i} V_f} \\ \frac{\alpha_{f_i} A_{exch_{int_f}} (T_{f_i} - T_{w_{int_i}}) + \alpha_{g_i} A_{exch_{int_g}} (T_{g_i} - T_{w_{int_i}})}{\rho_{w_{int}} V_{w_{int}}} \\ \frac{\dot{m}_g c_{p_g} (T_{g_i}) (T_{g_{i-1}} - T_{g_i}) - \alpha_{g_i} [A_{exch_{int_g}} (T_{g_i}^* - T_{w_{int_i}}) - A_{exch_{ext_g}} (T_{g_i} - T_{w_{ext_i}})]}{\rho_{g_i} V_{g_i} c_{p_g} (T_{g_i})} \\ \frac{\alpha_{amb} A_{exch_{ext_{amb}}} (T_{amb} - T_{w_{ext_i}}) + \alpha_{g_i} A_{exch_{ext_g}} (T_{g_i} - T_{w_{ext_i}})}{\rho_{w_{ext}} V_{w_{ext}}} \end{bmatrix}$$

Control objective

- One key parameter to control is the working fluid superheat level at the expansion machine inlet.
- Even more critical when using a kinetic expander.
- Reduce the deviation of the superheat around its set point allow to have safe and efficient operation.

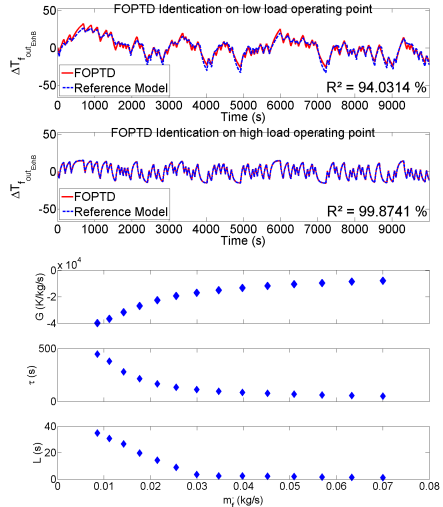


Identification

- Dynamic relation between u and y can be described around an operating point by a first order plus time delay (FOPTD):

$$\frac{y(s)}{u(s)} = \frac{G}{1 + \tau s} e^{-D s}, \quad (2)$$

- System behavior is highly non linear which is proven by the high variation in FOPTD parameters.
- Linear time invariant controller will hardly achieve the control objective with good performance under transient driving cycle.



Piecewise linear approach

- Multi linear model approach consists into identifying a bank of linear models around different relevant operating points and combine them by means of a weighting scheme.
- The global model output is obtained by

$$y_{g,k} = \sum_{i=1}^N y_{i,k} W_{i,k} \quad (3)$$

- Key design issue is on the selection of the good model(s) in the bank.
- The modeling error of the i^{th} model at the current time t_k is defined by:

$$\epsilon_{i,k} = y_{p,k} - y_{i,k}. \quad (4)$$

Weighting scheme

Bayesian recursive scheme

$$p_{i,k} = \frac{\exp(-\frac{1}{2}\epsilon_{i,k}K\epsilon_{i,k}^T p_{i,k-1})}{\sum_{m=1}^N (\exp(-\frac{1}{2}\epsilon_{m,k}K\epsilon_{m,k}^T p_{m,k-1}))}, \quad (5)$$

$$W_{i,k} = \begin{cases} \frac{p_{i,k}}{\sum_{m=1}^N p_{m,k}} & \text{for } p_{i,k} > \delta \\ 0 & \text{for } p_{i,k} < \delta \end{cases} \quad (6)$$

where K is a vector and δ a scalar.

Developed scheme

$$\tilde{\epsilon}_{i,k} = \frac{\epsilon_{i,k}^2}{\sum_{m=1}^N \epsilon_{m,k}^2}, \quad (7)$$

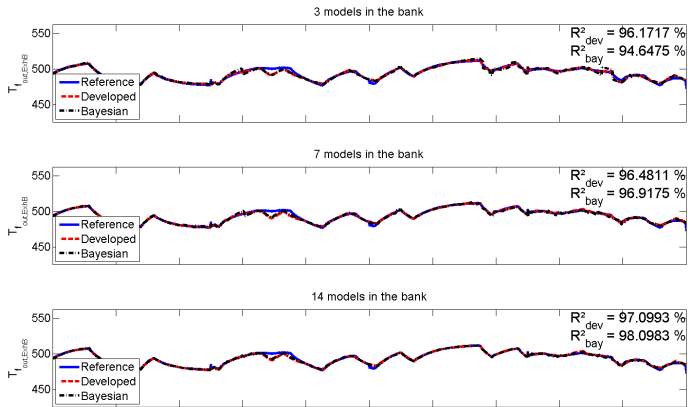
$$X_{i,k} = (1 - \tilde{\epsilon}_{i,k}) \prod_{j \neq i, j=1}^{j=N} \tilde{\epsilon}_{j,k}, \quad (8)$$

$$\tilde{X}_{i,k} = \frac{X_{i,k}}{\sum_{m=1}^N X_{m,k}}. \quad (9)$$

$$W_{i,k} = \frac{1}{1 + Ts} \tilde{X}_{i,k}, \quad (10)$$

Weighting scheme validation

Scheme to scheme comparison



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^{th} cell can be written:

$$\left\{ \begin{array}{l} 0 \\ \frac{\partial T_{w_{int_i}}}{\partial t} \\ 0 \\ \frac{\partial T_{w_{ext_i}}}{\partial t} \end{array} \right. = \begin{array}{l} \dot{m}_f (h_{f_{i-1}} - h_{f_i}) + \dot{Q}_{f_{int_i}} \\ \dot{Q}_{f_{int_i}} + \dot{Q}_{g_{int_i}} \\ \dot{m}_g c_{p_g} (T_{g_{i-1}} - T_{g_i}) + \dot{Q}_{g_{int_i}} + \dot{Q}_{g_{ext_i}} \\ \dot{Q}_{g_{ext_i}} + \dot{Q}_{amb_{ext_i}} \end{array} \quad (11)$$

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

$$U_{feedforward} = \frac{\sum_{i=1}^N \dot{Q}_{f_{int_i}}}{h_{f_L} - h_{f_0}}. \quad (12)$$

Methodology

- Baseline for all controllers comparison is a gain scheduled PID.
- Each controller performance is assessed on a relevant driving cycle in simulation.
- Pump and expansion machine models are added:

- Pump model:

$$\dot{m}_f = \rho_{f,in} \frac{N_{pump}}{60} C_{c_{pump}} \eta_{vol,pump} \quad (13)$$

- Expansion machine model:

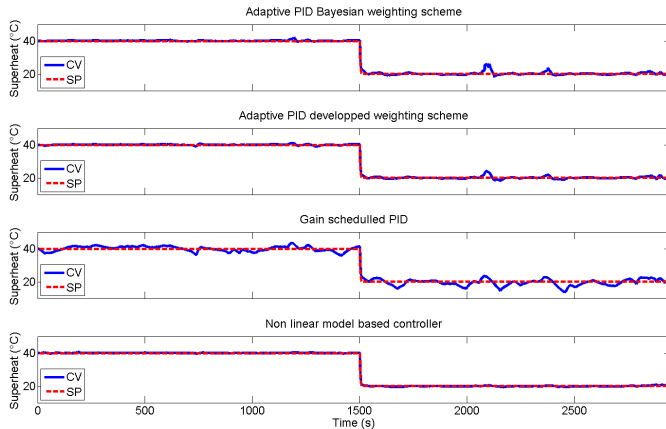
$$\dot{m}_f = k_{eq} \sqrt{\rho_{f,in} P_{f,in} \left(1 - \frac{P_{f,in}^{-2}}{P_{f,out}} \right)}. \quad (14)$$

- Detailed model of the evaporators experimentally validated (see companion paper).
- The absolute controller performance is assessed through the associated integral absolute error (IAE):

$$IAE = \int_0^{t_{sim}^{final}} |CV(t) - SP(t)| dt. \quad (15)$$

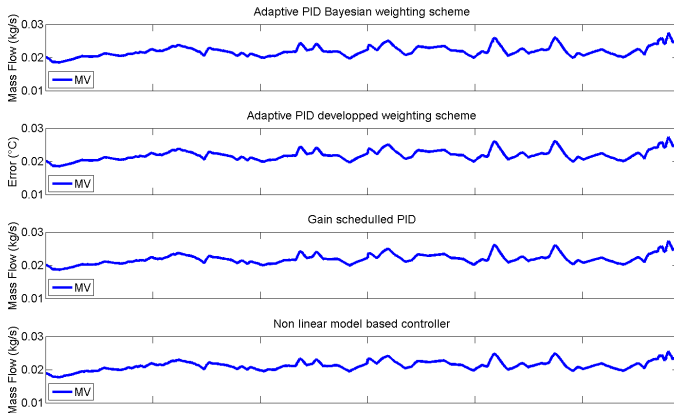
Tracking error

Controller to controller comparison



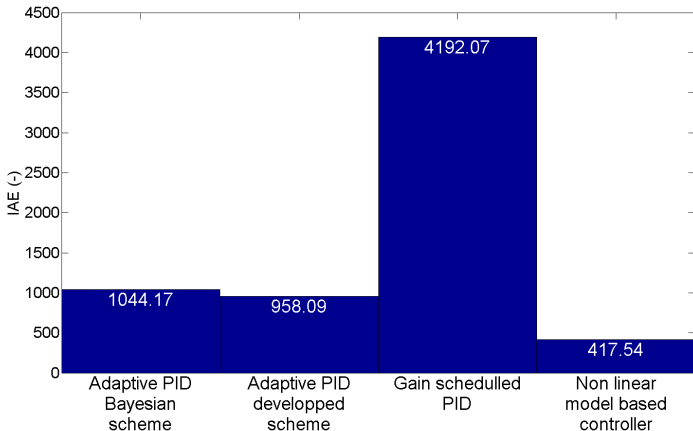
Manipulated variable

Controller to controller comparison



Controller performance

Controller to controller comparison



Conclusion and next steps

Conclusion

- Control strategies for Rankine cycle based heat recovery system are presented.
- All strategies are compliant with classical automotive integration constraints.
- A weighting scheme for a piecewise linear approach has been developed and validated.

Next steps

- Experimental validation.
- Robustness study.

Contacts and discussion

Authors

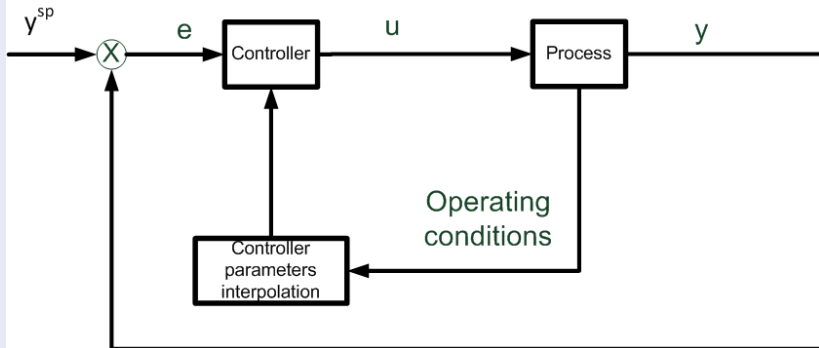
- Vincent GRELET: greletv@live.com
- Pascal DUFOUR: dufour@lagep.univ-lyon1.fr
- Madiha NADRI: nadri@lagep.univ-lyon1.fr
- Vincent LEMORT: vincent.lemort@ulg.ac.be
- Thomas REICHE: thomas.reiche@volvo.com

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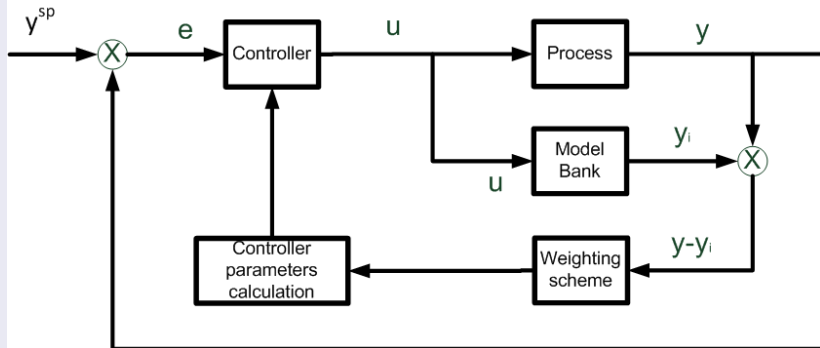
Implemented controller

Gain scheduled PID

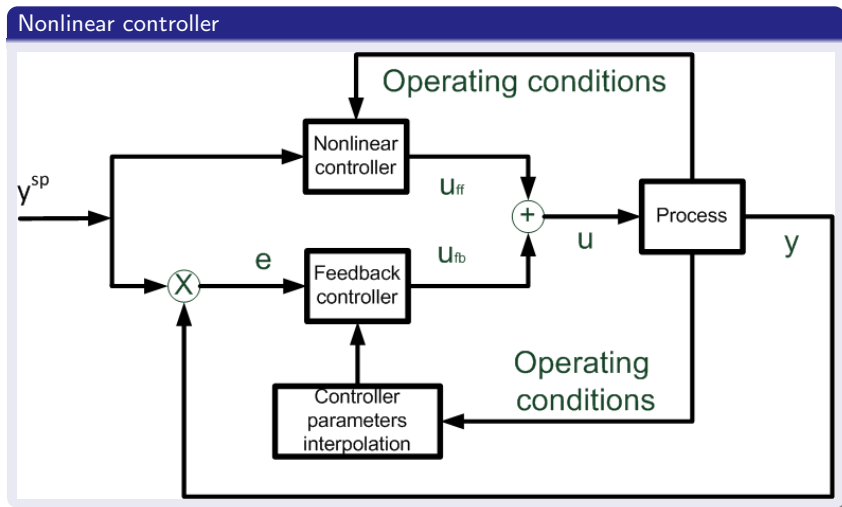


Implemented controller

Adaptive PID

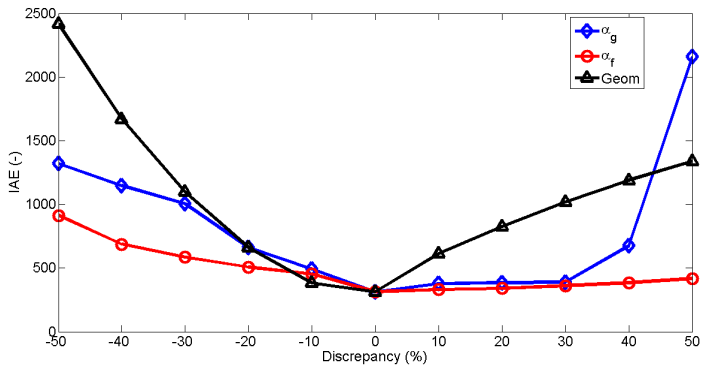


Implemented controller



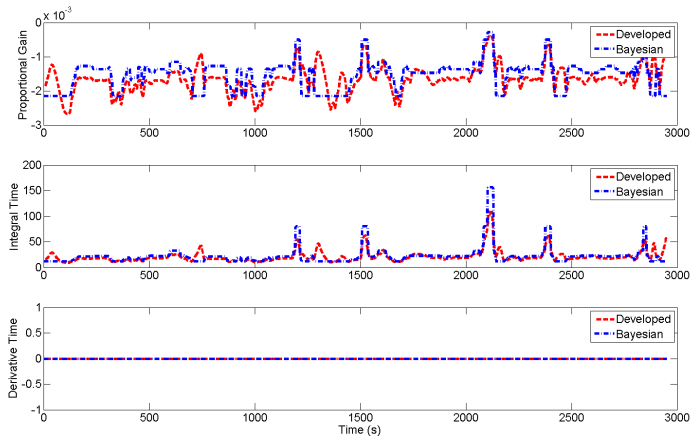
Controller performance

Model uncertainties



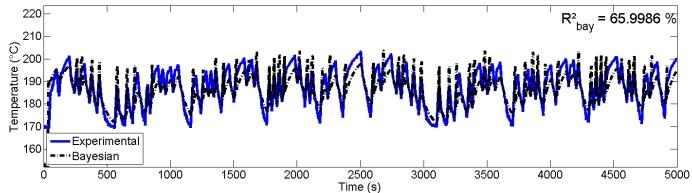
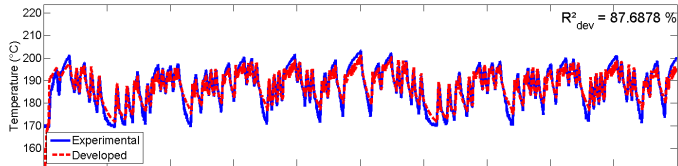
Controller performance

PID parameters



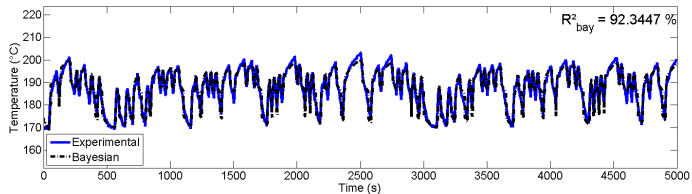
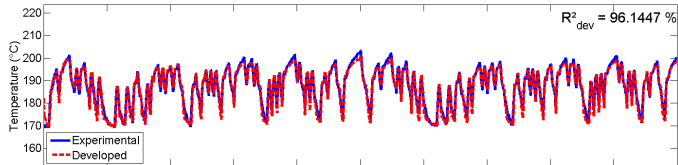
Piecewise linear approach: experimental validation

$N = 4$



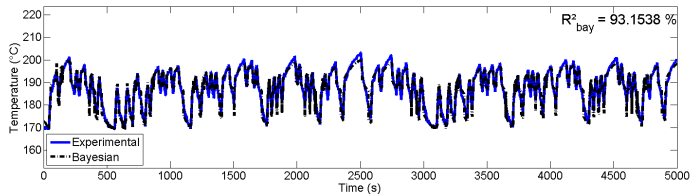
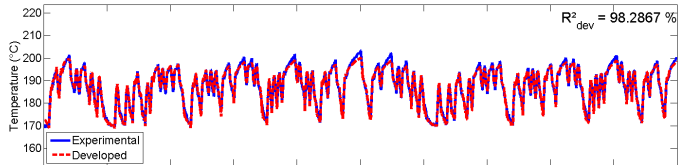
Piecewise linear approach: experimental validation

$N = 8$



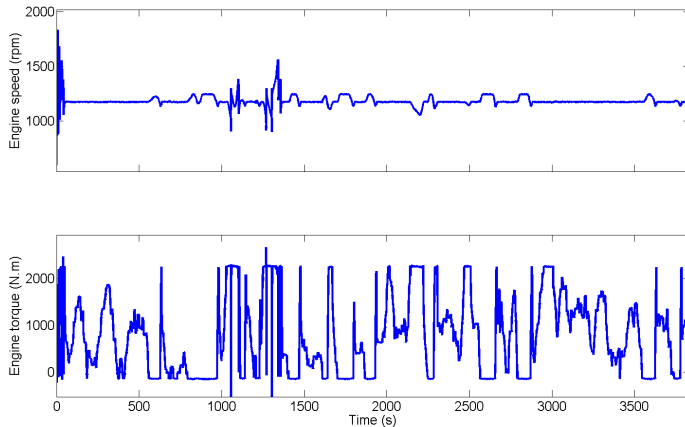
Piecewise linear approach: experimental validation

$N = 12$



Adaptive PID strategy: experimental validation

Duty cycle



Adaptive PID strategy: experimental validation

Tracking error

