

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

Vincent GRELET<sup>1,2,3</sup>, Thomas REICHE<sup>1</sup>, Madiha NADRI<sup>2</sup>, Pascal DUFOUR<sup>2</sup> and Vincent LEMORT<sup>3</sup>

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

<sup>2</sup>Université de Lyon, Lyon F-69003, Université Lyon 1, CNRS UMR 5007, Laboratory of Process Control and Chemical Engineering (LAGEP), Villeurbanne 69100, France

<sup>3</sup>LABOTHAP, University of Liege, Campus du Sart Tilman Bat. B49 B4000 Liege, Belgium

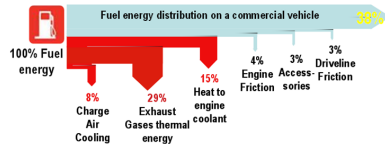
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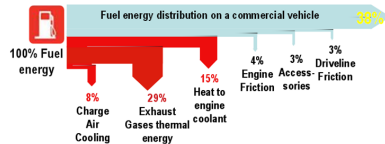
## Context and motivations

In nowadays heavy duty engines, a major part of the chemical energy contained in the fuel is released to the ambient through heat.



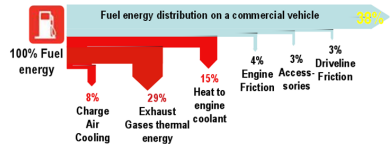
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- Waste heat recovery based on the Rankine cycle is a promising technique to increase fuel efficiency.



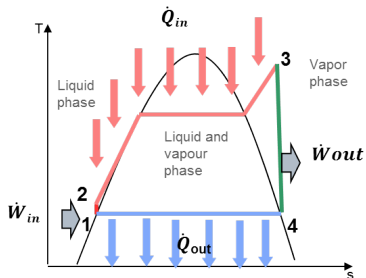
## Context and motivations

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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.



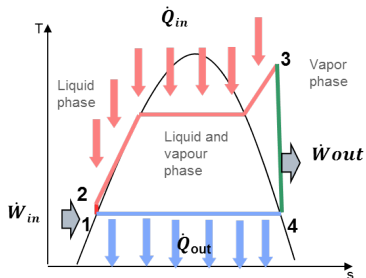
## Waste heat recovery Rankine cycle based

- Rankine cycle is widely known and used for power generation.
- It is based on four basic transformations:



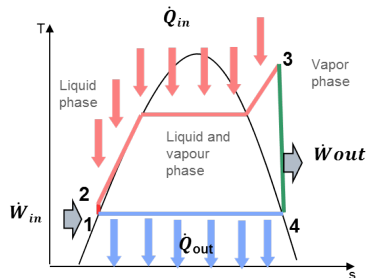
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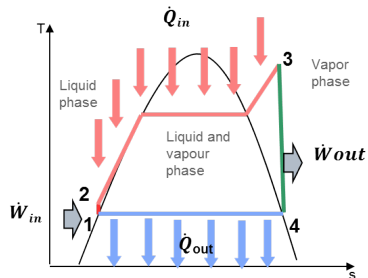
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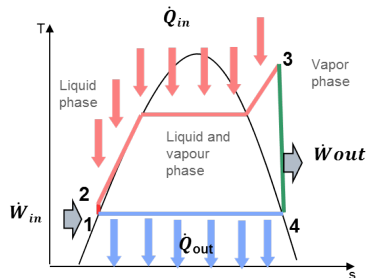
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  - It expands from evaporating to condensing pressure ( $3 \rightarrow 4$ ).

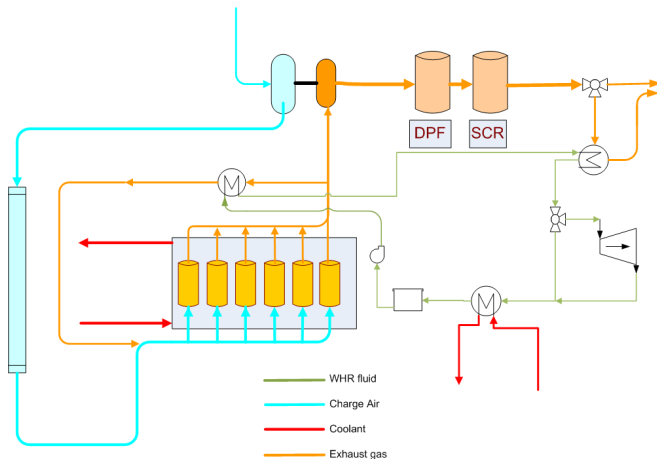


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  - It is then pre-heat, vaporize and superheat ( $2 \rightarrow 3$ ).
  - It expands from evaporating to condensing pressure ( $3 \rightarrow 4$ ).
  - It condenses and goes back to liquid state ( $4 \rightarrow 1$ ).



## Studied system



## 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

$$A_{cross,f} \frac{\partial \rho_f h_f}{\partial t} + \frac{\partial \dot{m}_f h_f}{\partial z} + \dot{q}_{f,int} = 0. \quad (1)$$

- Internal pipe wall

$$\dot{q}_{f,int} + \dot{q}_{g,int} = \frac{\partial m_{w,int} c_{p_w,int} T_{w,int}}{\partial t}. \quad (2)$$

- External fluid

$$\frac{\partial \dot{m}_g c_{p_g} T_g}{\partial z} + \frac{\partial \dot{m}_g c_{p_g} T_g}{\partial t} + \dot{q}_{g,int} + \dot{q}_{g,ext} = 0. \quad (3)$$

- External pipe wall

$$\dot{q}_{g,ext} + \dot{q}_{amb,ext} = \frac{\partial m_{w,ext} c_{p_w,ext} T_{w,ext}}{\partial t}. \quad (4)$$

## Heat transfer

### Heat transfer coefficients

$$\alpha_g = \alpha_{ref,g} \dot{m}_g^{n_g} \quad (5)$$

$$\alpha_{f,liq} = \alpha_{ref,f,liq} \dot{m}_f^{n_{f,liq}} \quad (6)$$

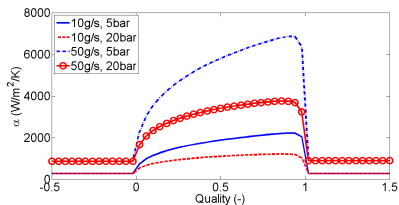
$$\alpha_{f,2\varphi} = \alpha_{f,liq} \dots$$

$$\dots \left\{ (1-q)^{0.01} \left[ (1-q) + 1.2q^{0.4} \frac{\rho_{f,sat,liq}^{0.37}}{\rho_{f,sat,vap}} \right]^{-2.2} + \dots \right. \\ \left. \dots q^{0.01} \left[ \frac{\alpha_{f,vap}}{\alpha_{f,liq}} \left( 1 + 8(1-q)^{0.7} \frac{\rho_{f,sat,liq}^{0.67}}{\rho_{f,sat,vap}} \right) \right]^{-2} \right\}^{-0.5} \quad (7)$$

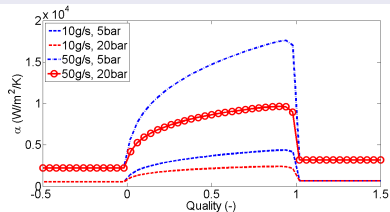
$$\alpha_{f,vap} = \alpha_{ref,f,vap} \dot{m}_f^{n_{f,vap}} \quad (8)$$

## Heat transfer

### Heat transfer EGR boiler



### Heat transfer exhaust boiler



## Working fluid properties

### Working fluid properties models

- Temperature:

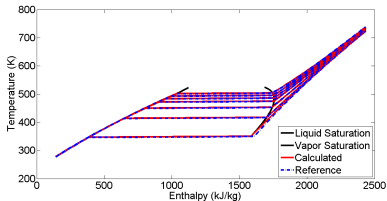
$$T_f = \begin{cases} a_{T,liq} h_f^2 + b_{T,liq} h_f + c_{T,liq} & \text{if } h_f \leq h_{sat,liq} \\ T_{sat,liq} + q (T_{sat,vap} - T_{sat,liq}) & \text{if } h_{sat,liq} \geq h_f \geq h_{sat,vap} \\ a_{T,vap} h_f^2 + b_{T,vap} h_f + c_{T,vap} & \text{if } h_f \geq h_{sat,vap} \end{cases} \quad (9)$$

- Density

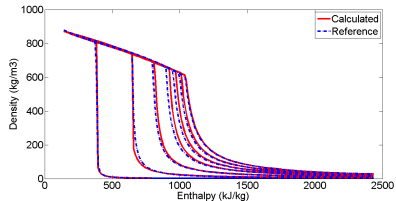
$$\rho_f = \begin{cases} a_{\rho,liq} h_f^2 + b_{\rho,liq} h_f + c_{\rho,liq} & \text{if } h_f \leq h_{sat,liq} \\ \frac{1}{a_{\rho,2\varphi} h_f + b_{\rho,2\varphi}} & \text{if } h_{sat,liq} \geq h_f \geq h_{sat,vap} \\ a_{\rho,vap} h_f^2 + b_{\rho,vap} h_f + c_{\rho,vap} & \text{if } h_f \geq h_{sat,vap} \end{cases} \quad (10)$$

## Working fluid properties

### Temperature model validation



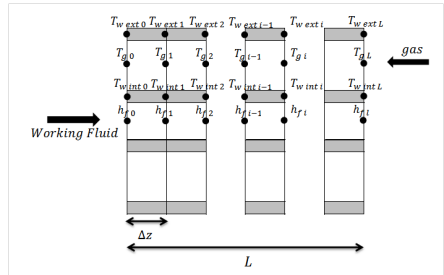
### Density model validation





## Discretization

- 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:  $\dot{m}_{g,L}$ ,  $T_{g,L}$ ,  $h_{f,0}$ ,  $P_{f,0}$ .



## Discretization

- The system of equations defining the response of the  $i^{\text{th}}$  cell of the discretized model is:

$$\dot{x}_i = f_i(x_i, u), \quad (11)$$

$$\text{where: } u = [\dot{m}_{f,0} \quad P_{f,0} \quad h_{f,0} \quad \dot{m}_{g,L} \quad T_{g,L}], \quad (12)$$

$$x_i = [h_{f,i} \quad T_{w,int,i} \quad T_{g,i} \quad T_{w,ext,i}], \quad (13)$$

$$f_i(x_i, u) = \left[ \begin{array}{c} \frac{\dot{m}_f (h_{f,i-1} - h_{f,i}) - \alpha_{f,i} A_{exch,f,int} (T_{f,i} - T_{w,int,i})}{\rho_{f,i} V_f} \\ \frac{\alpha_{f,i} A_{exch,f,int} (T_{f,i} - T_{w,int,i}) + \alpha_{g,i} A_{exch,g,int} (T_{g,i} - T_{w,int,i})}{\rho_{w,int} V_{w,int}} \\ \frac{\dot{m}_g c_{p,g} (T_{g,i-1} - T_{g,i}) - \alpha_{g,i} [A_{exch,g,int} (T_{g,i} - T_{w,int,i}) - A_{exch,g,ext} (T_{g,i} - T_{w,ext,i})]}{\rho_{g,i} V_g c_{p,g}} \\ \frac{\alpha_{amb} A_{exch,amb,ext} (T_{amb} - T_{w,ext,i}) + \alpha_{g,i} A_{exch,g,ext} (T_{g,i} - T_{w,ext,i})}{\rho_{w,ext} V_{w,ext}} \end{array} \right] \quad (14)$$

## Implementation constraint

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

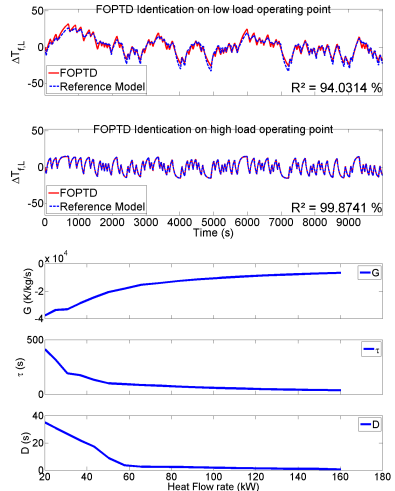
- Simulink based environment.
- Controller must be discretized in time.
- Backward Euler integration scheme has to be used with a sample time of 20ms.
- Calculation must stay as simple as possible (problems have to be rescaled to avoid the use of high computational capacity demand functions).

## 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:

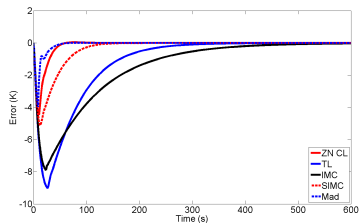
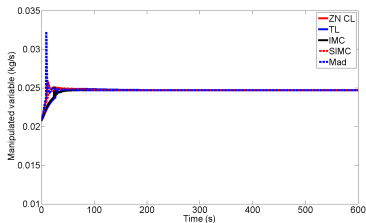
$$\frac{\Delta T_{f,L}}{\Delta \dot{m}_f} = \frac{G}{1 + \tau S} e^{-D_s} \quad (15)$$

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



## 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  $i^{\text{th}}$  cell can be written:

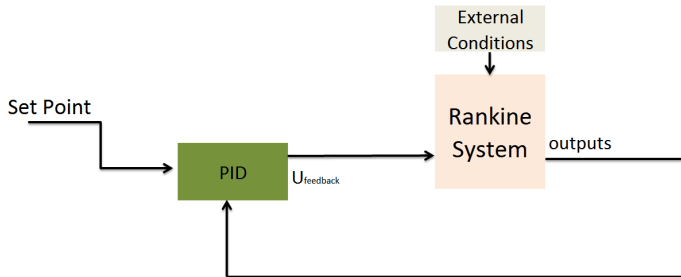
$$\left\{ \begin{array}{l} 0 \\ \frac{\partial T_{w_{int}i}}{\partial t} \\ 0 \\ \frac{\partial T_{w_{ext}i}}{\partial t} \end{array} \right. = \begin{array}{l} \dot{m}_f (h_{f_{i-1}} - h_{f_i}) + \dot{Q}_{f_{int}i} \\ \dot{Q}_{f_{int}i} + \dot{Q}_{g_{int}i} \\ \dot{m}_g c_{p_g} (T_{g_{i-1}} - T_{g_i}) + \dot{Q}_{g_{int}i} + \dot{Q}_{g_{ext}i} \\ \dot{Q}_{g_{ext}i} + \dot{Q}_{amb_{ext}i} \end{array} \quad (16)$$

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

$$U_{feedforward} = \frac{\sum_{i=1}^N \dot{Q}_{f_{int}i}}{h_{f_0} - h_{f_L}} \quad (17)$$

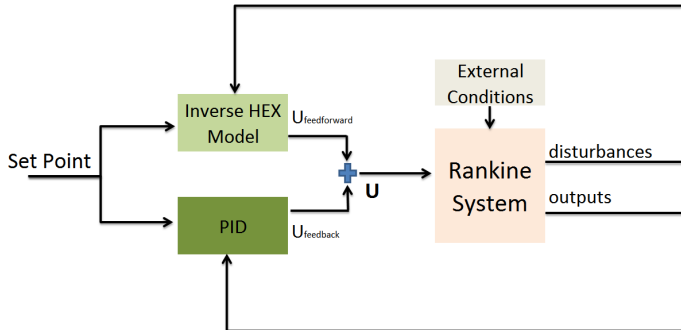
## Controllers structure

### Feedback controller



## Controllers structure

### Nonlinear controller





## Simulation environment

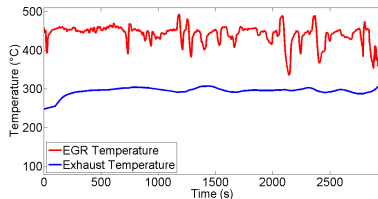
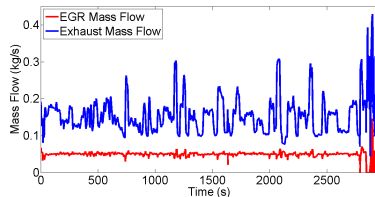
Pump and expansion machine models are added to represent the high pressure part of the Rankine system.

- Pump model:

$$\dot{m}_f = \rho_{f,in} \frac{N_{pump}}{60} C_{c,pump} \eta_{vol,pump} \cdot (18)$$

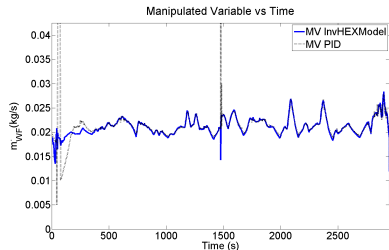
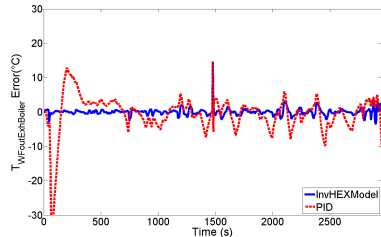
- Expansion machine:

$$\dot{m}_f = k_{eq} \sqrt{\rho_{f,in} P_{f,in} \left( 1 - \frac{P_{f,in}}{P_{f,out}} \right)^{-2}} \cdot (19)$$



## Controller comparison

- Initial set point and disturbances change are not handle by PID controller.
- The non linear controller reduce the deviation from  $\pm 10^{\circ}\text{C}$  with the PID to  $\pm 3^{\circ}\text{C}$ .



## Conclusion and next steps

### 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](mailto:vincent.grelet@volvo.com)
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