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You downloaded this document from the CNRS open archives server, on the webpages of Pascal Dufour: <u>http://hal.archives-ouvertes.fr/DUFOUR-PASCAL-C-3926-2008</u> Control Design for an Automotive Turbine Rankine Cycle System based on Nonlinear State Estimation

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ORC for transport application

The main differences with stationary applications lie in the highly transient behaviour of the hot source, depending on driving conditions.



1 Rankine cycle

- System description
- Control-oriented model

2 Closed-loop design • Observer design

• Control design





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Context	Rankine cycle	Closed-loop design	Closed loop evaluation	Conclusion
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Therm	odvnamic cvc	e		





- O Vaporization
- 2 Expansion
- Condensation
- Compression

Superheating SH

- Definition: SH is the "distance" in kelvin of the fluid from the evaporation temperature.
- Effective SH control is a key issue for: cycle efficiency, component safety.



Main actuators

- evaporator by-pass: lets a fraction of exhaust gas feeding ORC.
- pump: circulates the working fluid.

Control objective

Respond to a power production demand while ensuring an effective SH control.

Context	Rankine cycle	Closed-loop design	Closed loop evaluation	Conclusion
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ORC:	high pressure	part		

First model reduction

- Fluid conditions in low pressure part can be seen as a (slow) disturbance.
- A power production demand is then equivalent to a high pressure demand.



Known disturbances:

- Fluid temperature at pump (measured).
- Fluid pressure at turbine outlet (measured).
- Exhaust mass flow m_{exh} (estimated).
- Exhaust temperature: T_{exh} (measured).



A low-order, but realistic, model of evaporator can be obtained via MB (see e.g [Jensen, 2003]). method.



Thermodynamic variables

- fluid pressure p (homogenous along the evaporator)
- fluid enthalpies *h_i* (for each zone)
- wall temperatures: T_{w,i}



Dynamics of the reduced model: wall energy balance

$$m_{w} c_{w} \frac{d}{dt} T_{w,i} = \dot{Q}_{exh,i} - \dot{Q}_{f,i},$$

where $\dot{Q}_{exh,i} = \dot{m}_{exh} c_{exh} \left(1 - exp(-\frac{\alpha_{exh} S_{exh}}{\dot{m}_{exh} c_{exh}})\right) (T_{exh} - T_{w,i})$

Context	Rankine cycle	Closed-loop design	Closed loop evaluation	Conclusion
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Explici	t model			

Assuming that SH is perfectly regulated¹ at a constant value by the pump mass- ow (u_1) , the reduced model can be written in the following semi-explicit form:

$$\begin{cases} \dot{x} = f(x,p) + u_2 g(x,t), \\ \varphi(x,p) = 0. \end{cases}$$
(1)

Proposition

There exists
$$\epsilon > 0$$
 such that $\frac{\partial \varphi}{\partial p}$ has a full rank on the tubular neighbourhood

$$\Omega_{\epsilon} = \{ (x, p) \in \mathbb{R}^{3+1}; \| \varphi(x, p) \| < \epsilon \}.$$

Then, system (1) can be written in the following explicit form: $\begin{cases}
\dot{x} = f(x,p) + u_2 g(x,t) \\
\dot{p} = -\left(\frac{\partial \varphi}{\partial p}|_{x,p}\right)^{-1} \left(\frac{\partial \varphi}{\partial x}|_{x,p}\right) \times (f(x,p) + u_2 g(x,t)).
\end{cases}$ (2)

 1 [Peralez et al., 2013] showed experimentally that such assumption is realistic, even in transient driving conditions)

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An implicit extended Kalman filter² (EKF) for system (1) is given by:

$$\begin{cases} \dot{\hat{T}}_{w} = f(\hat{T}_{w}, \hat{p}) + u_{2} g(\hat{T}_{w}, \hat{p}) - SC^{T} R^{-1} (\hat{p} - p) \\ \Phi(\hat{T}_{w}, \hat{p}) = 0 \\ \dot{S} = AS + SA^{T} - SC^{T} R^{-1} C^{T} S + Q \\ S(0) = S(0)^{T} > 0, \end{cases}$$
(3)

where Q is a constant symmetric positive definite (SPD) matrix, R is a real positive constant and

$$A = \frac{\partial (f + u_2 g)}{\partial x}|_{(\hat{T}_w, \hat{p})}, \quad C = \varphi_p^{-1} \varphi_{T_w}^T.$$

²see [Åslund and Frisk, 2006]



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Context	Rankine cycle	Closed-loop design	Closed loop evaluation	Conclusion
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Pressure	control desi	gn		

Proposition

Let k > 0 then, the control

$$u_2(T_w, p, p^{SP}) = \frac{-\varphi_{T_w}^T f(T_w, p) + k(p^{SP} - p)}{\varphi_{T_w}^T g(T_w, t)},$$
(4)

asymptotically stabilizes p to the setpoint p^{SP} . Moreover, the input u_2 and the states of system (2) remain bounded.



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Closed loop evaluation

④ Conclusion

Context	Rankine cycle	Closed-loop design	Closed loop evaluation	Conclusion
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Realistic	driving con	ditions		

Experimental data for exhaust gas conditions that are representative of a long-haul truck mission were used:





A tight pressure set-point tracking is demonstrated as long as exhaust gas heat flow is sufficient.



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Context	Rankine cycle	Closed-loop design	Closed loop evaluation	Conclusion
Conclu	sion			

Summary

The proposed scheme combines

- a superheat controller,
- an additional nonlinear controller, allowing pressure set-point tracking or equivalently a tracking of power production demand.
- an implicit extended Kalman Filter for wall temperature estimations.

The proposed approach has been illustrated with success in presence of measurement noise, model uncertainties and state initial errors.

On-going work

- Experimental implementation.
- Theoretical proof of the asymptotic stability of the closed-loop using the observer.



