DYNAMIC MODELLING AND OPTIMIZED MODEL PREDICTIVE CONTROL STRATEGIES FOR THE ORGANIC RANKINE CYCLE

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Introduction

- ✓ Organic Rankine Cycle (ORC) : Small scale, lower temperature
- ✓ Application fields : Waste heat recovery, Solar sources, engine exhaust gases, biomass CHP, geothermy, ...
- ✓ Selection of the working fluid and optimization of the working conditions are key issues in waste heat recovery applications
- ✓ Dynamic models are required to define proper control strategies under transient conditions

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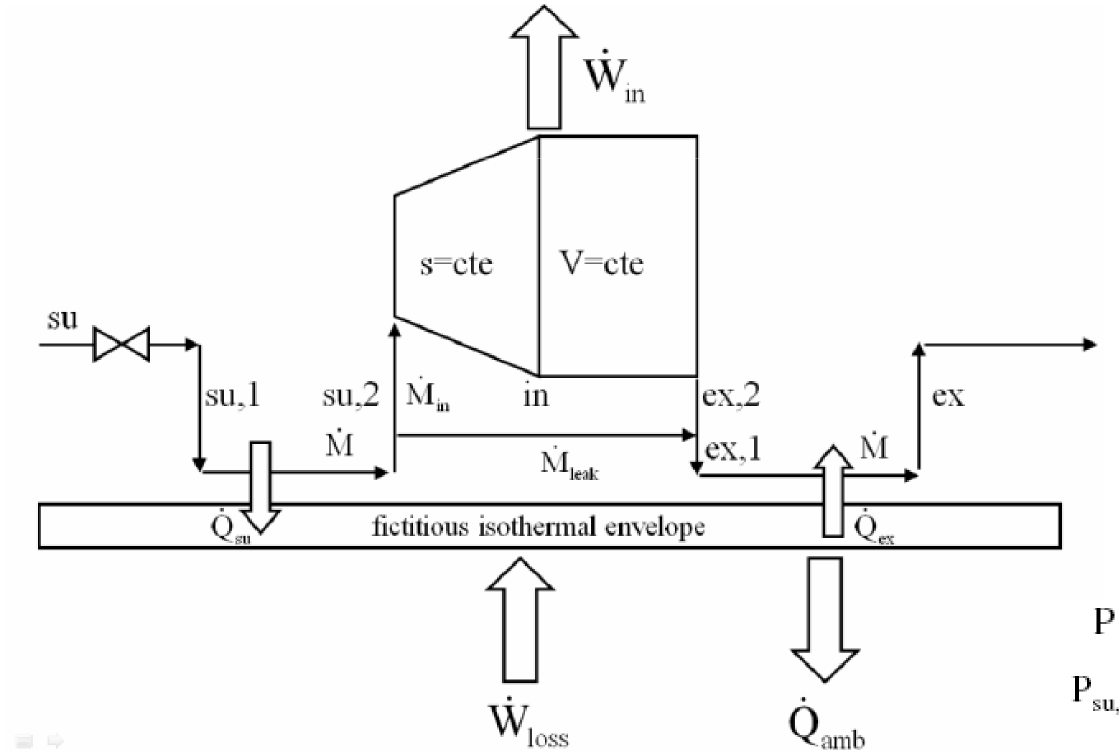
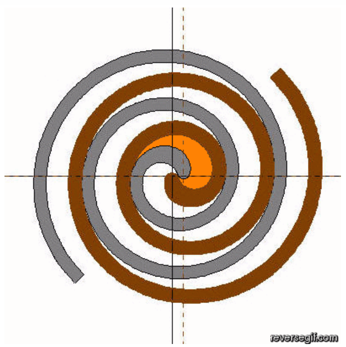
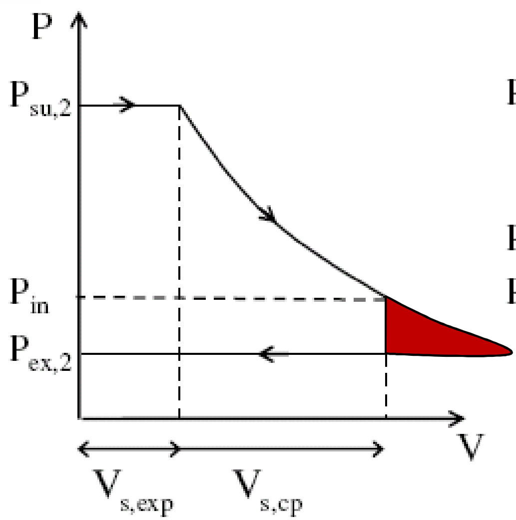
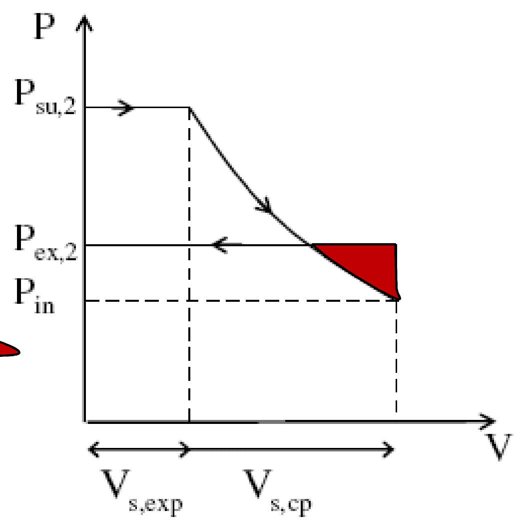
Volumetric expander model



- ✓ Heat transfers
- ✓ Friction
- ✓ Internal Leakage
- ✓ Pressure drops
- ✓ Built-in internal volume ratio
  - ⇒ Under and over-expansion

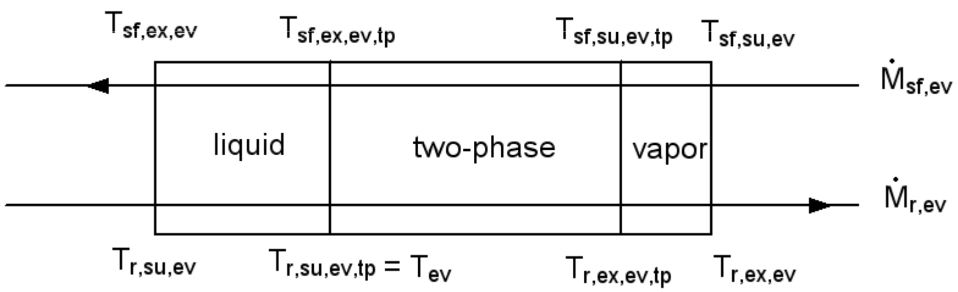






ORC cycle steady-state model

Plate Heat exchangers model:



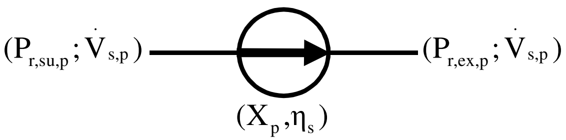
$$Nu = C \cdot Re^{n} \cdot Pr^{n}$$

$$h_{tp} = C \cdot \left(0.25 \cdot Co^{-0.45} \cdot FR_{l}^{0.25} + 75 \cdot Bo^{0.75}\right)$$

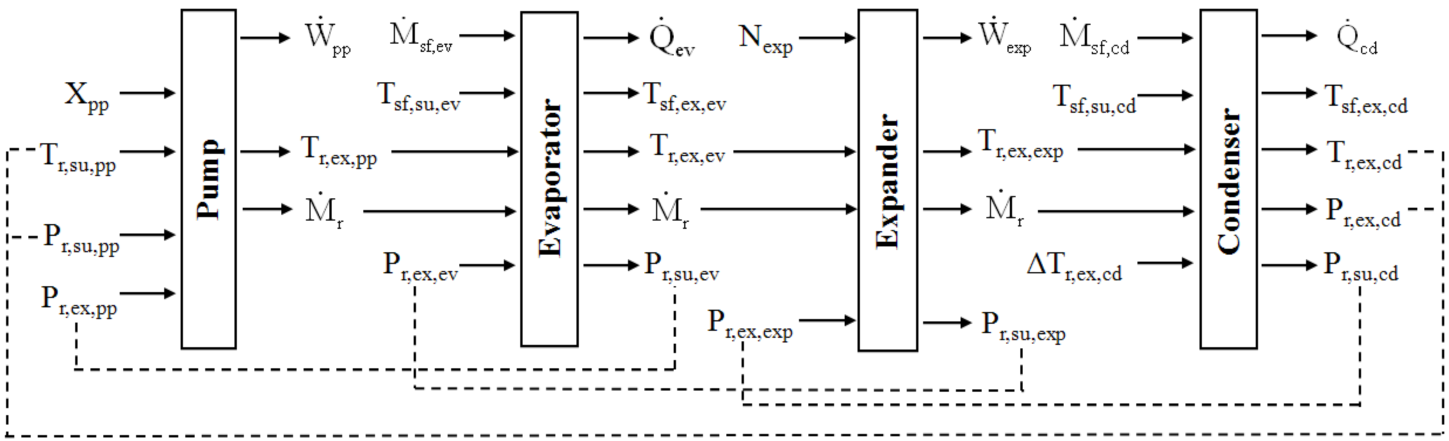
$$h_{tp,ev} = C \cdot h_{l} \cdot Bo^{0.5}$$

$$\Delta p = \frac{2 \cdot f \cdot G^{2}}{D_{h} \cdot \rho} \cdot L$$

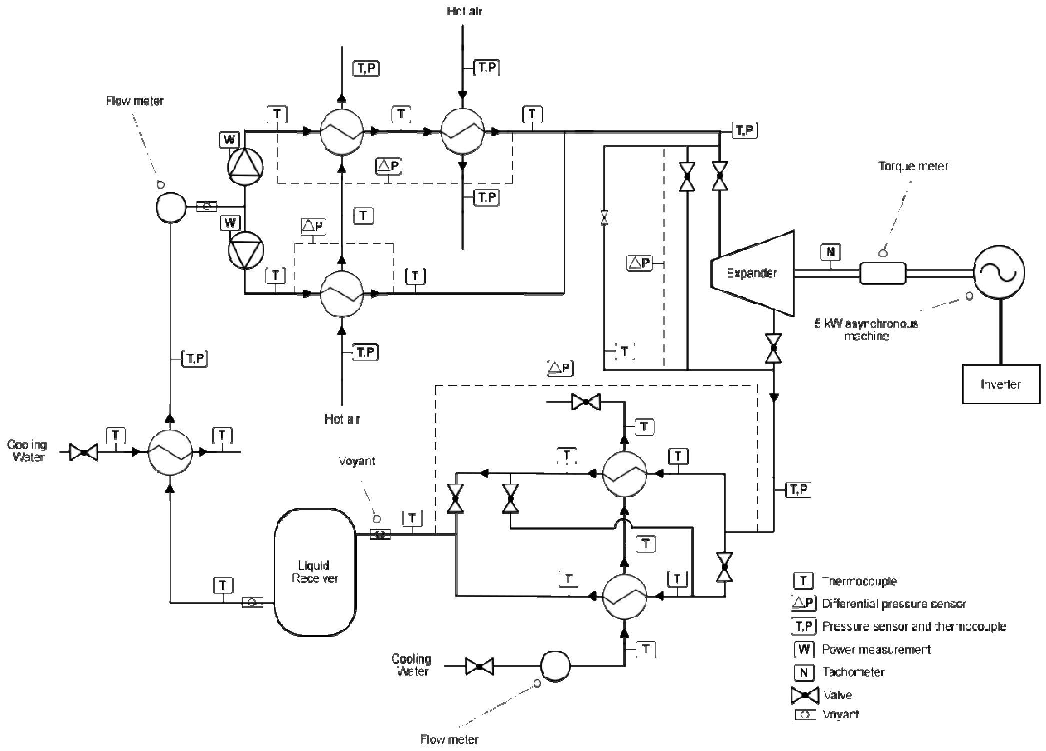
Pump model:

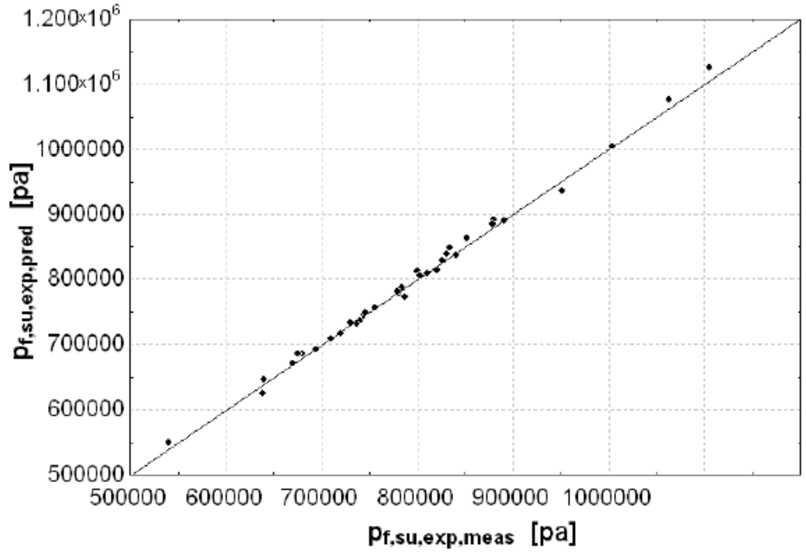


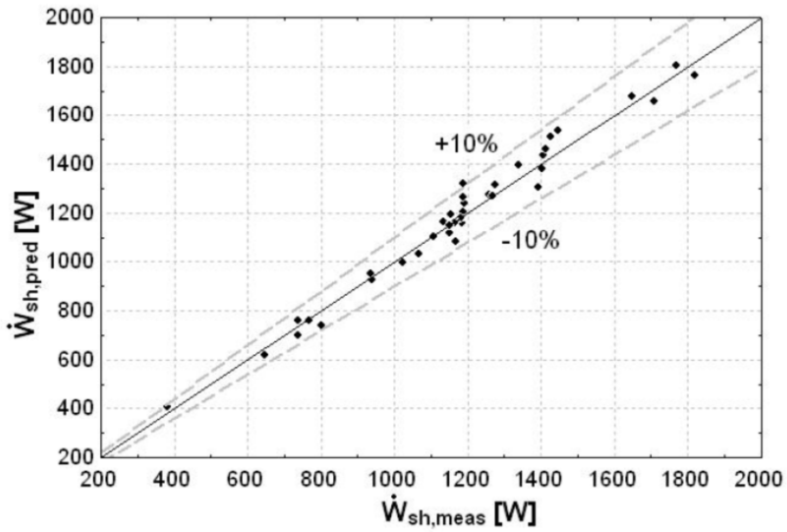
Cycle model:



Experimental validation







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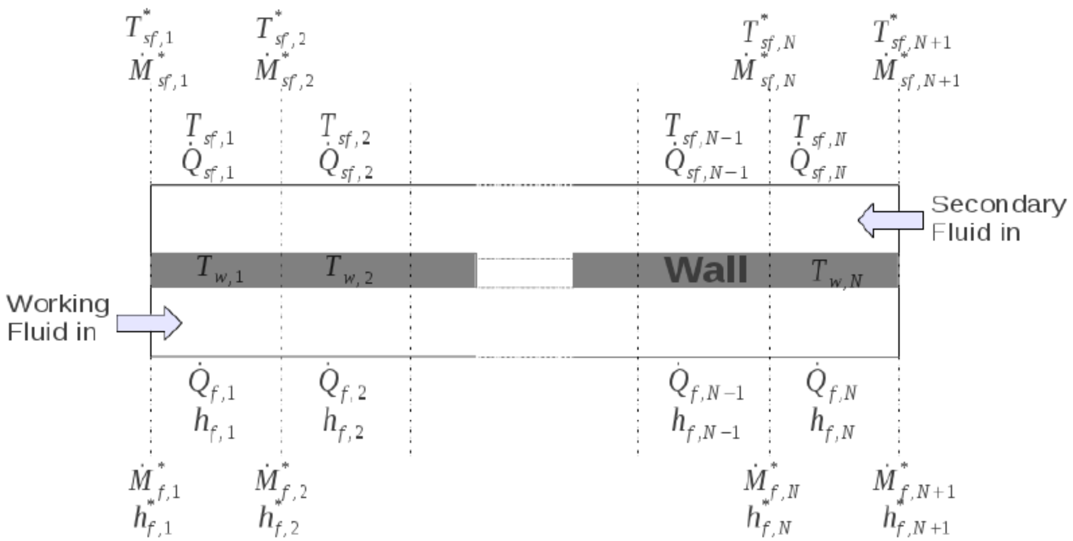
HEAT EXCHANGER MODEL



Simplified heat transfer and pressure drop laws:

$$U = U_n \cdot \left(\frac{\dot{M}}{\dot{M}_n} \right)^m$$

$$\Delta p = \frac{\dot{M}^2}{2 \cdot \rho \cdot A^2}$$

Conservation of energy:

$$V_i \cdot \rho_i \cdot \frac{\partial h_i}{\partial t} = \dot{M}^*_{i-1} \cdot (h^*_{i-1} - h_i) - \dot{M}^*_i \cdot (h^*_i - h_i) + \dot{Q}_i + V_i \cdot \frac{dp}{dt}$$

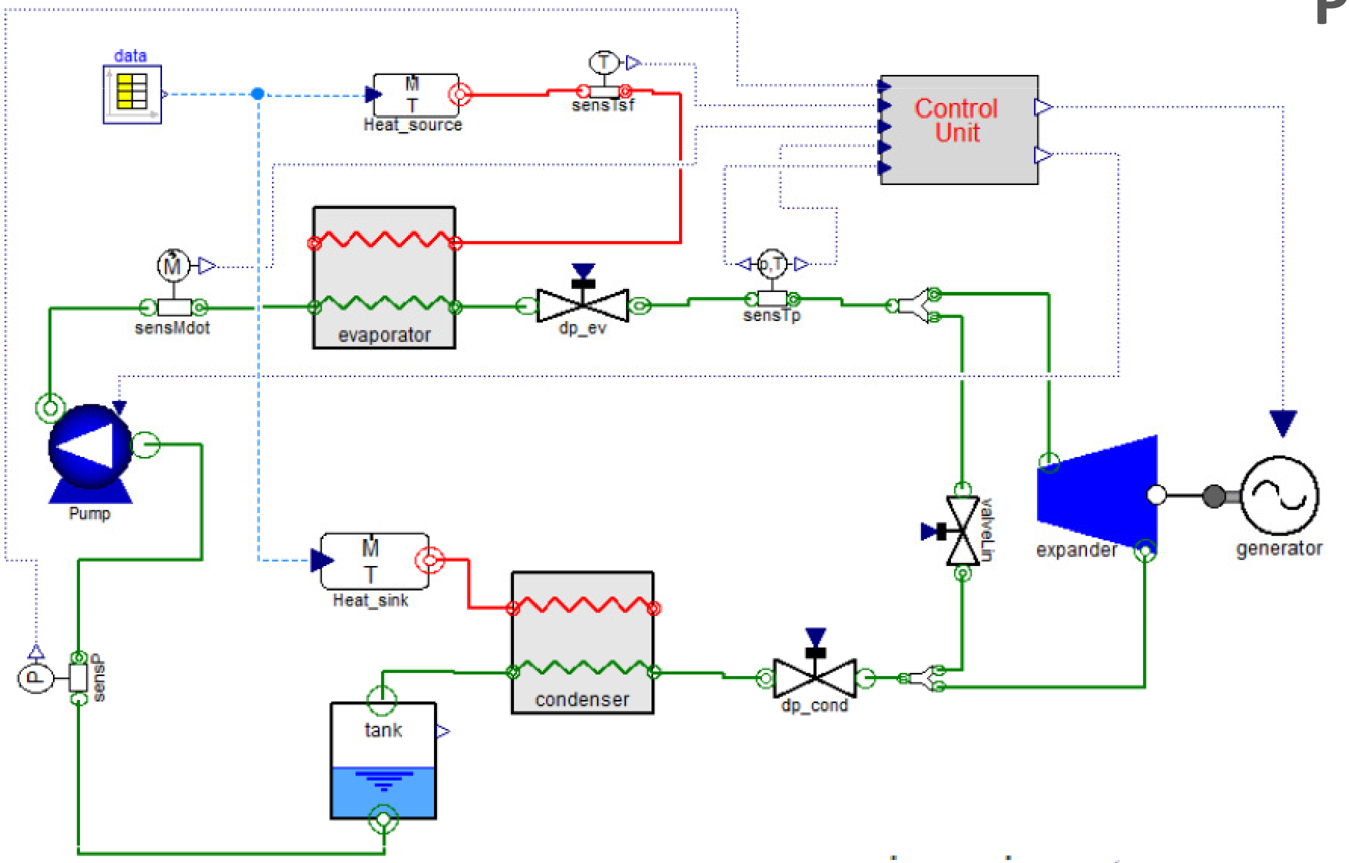
Conservation of mass:

$$\frac{dM_i}{dt} = V_i \cdot \left(\frac{\partial \rho}{\partial h} \cdot \frac{dh}{dt} + \frac{\partial \rho}{\partial p} \cdot \frac{dp}{dt} \right) = \dot{M}^*_i - \dot{M}^*_{i-1}$$

Metal wall:

$$c_w \cdot M_{w,i} \cdot \frac{dT_{w,i}}{dt} = \dot{Q}_{sf,i} - \dot{Q}_{f,i}$$

CYCLE MODEL



Performance indicators:

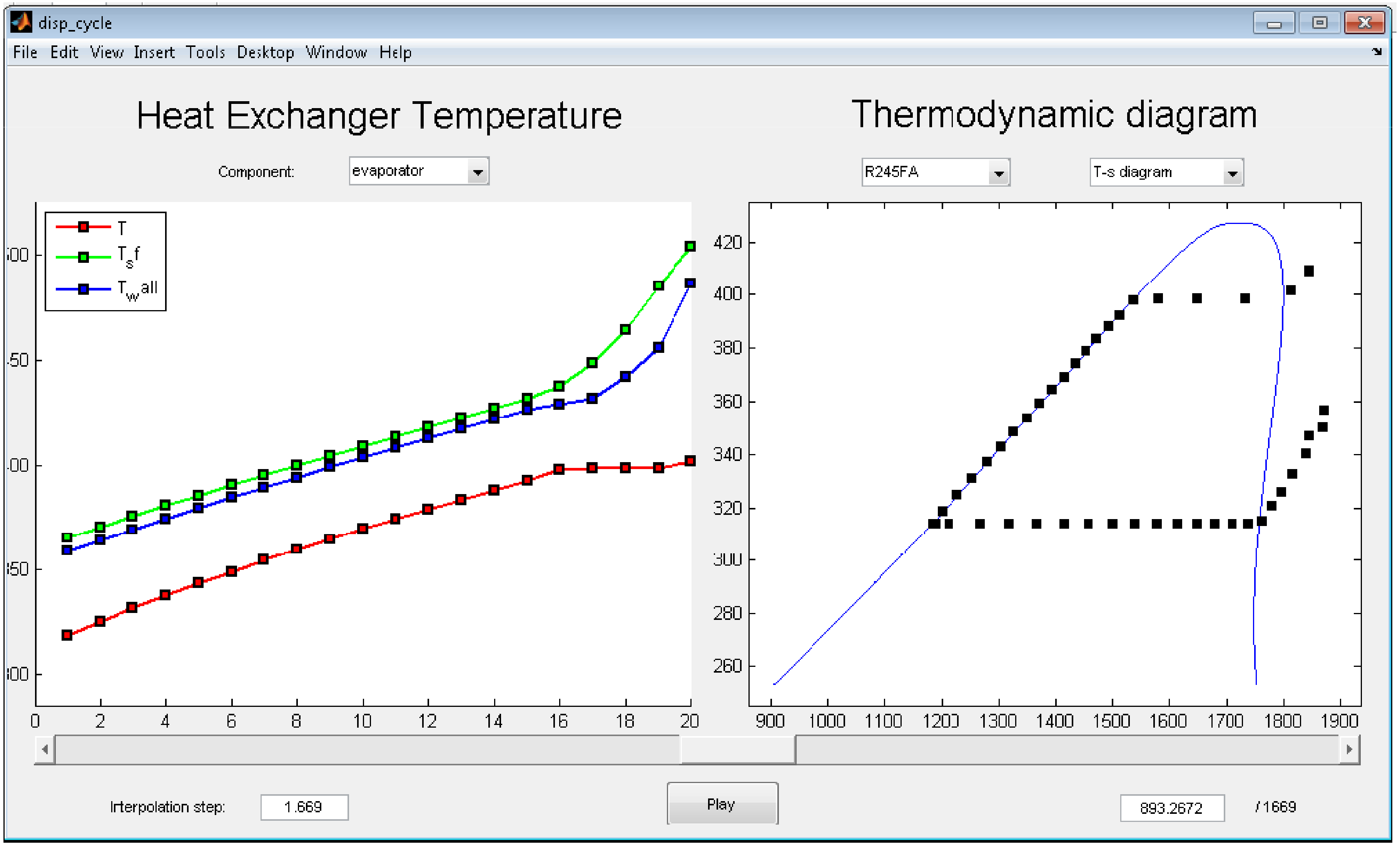
$$W_{net} = \int_{t_1}^{t_2} (\dot{W}_{exp} - \dot{W}_{pp})\, dt$$

$$W_{net} = \eta_{ORC} \cdot \int_{t_1}^{t_2} \dot{Q}_{ev}\, dt$$

$$W_{net} = \eta_{II} \cdot \int_{t_1}^{t_2} \dot{I}_{hf}\, dt$$

$$\dot{I}_{hf} = \dot{M}_{hf} \cdot [(h_{hf,su} - h_{hf,ref}) - T_{cf,su} \cdot (s_{hf,su} - s_{hf,ref})]$$

CYCLE DISPLAY



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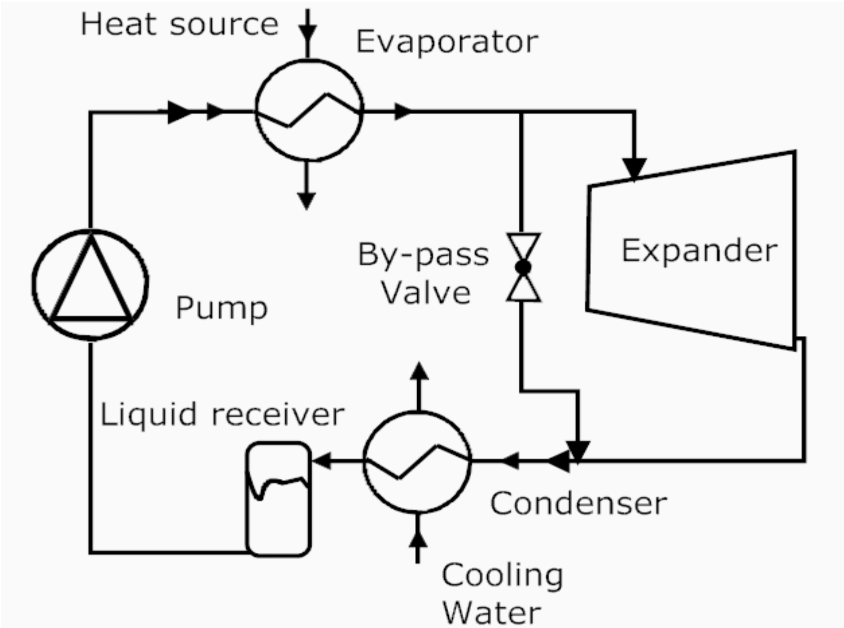
- **Cycle optimization and control**
- Model predictive control
- Conclusions

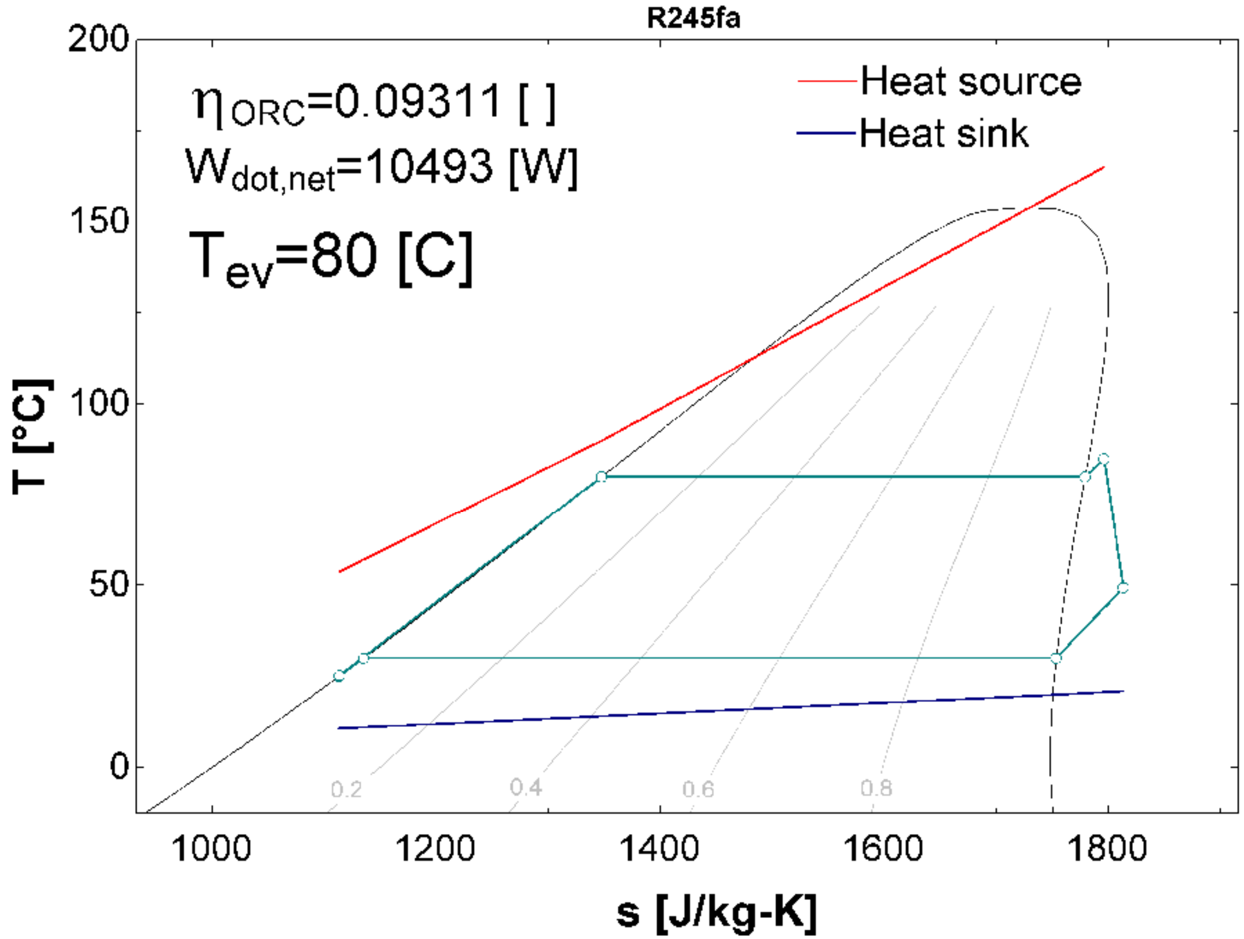
CONTROL STRATEGIES

Degrees of freedom:		Controlled variables:
$\dot{M}_{pp}$	→	$\Delta T_{ex,ev}$
$N_{rot,exp}$	→	T_{ev}



Optimal working conditions

⇨ **Main optimization parameter : evaporation temperature**

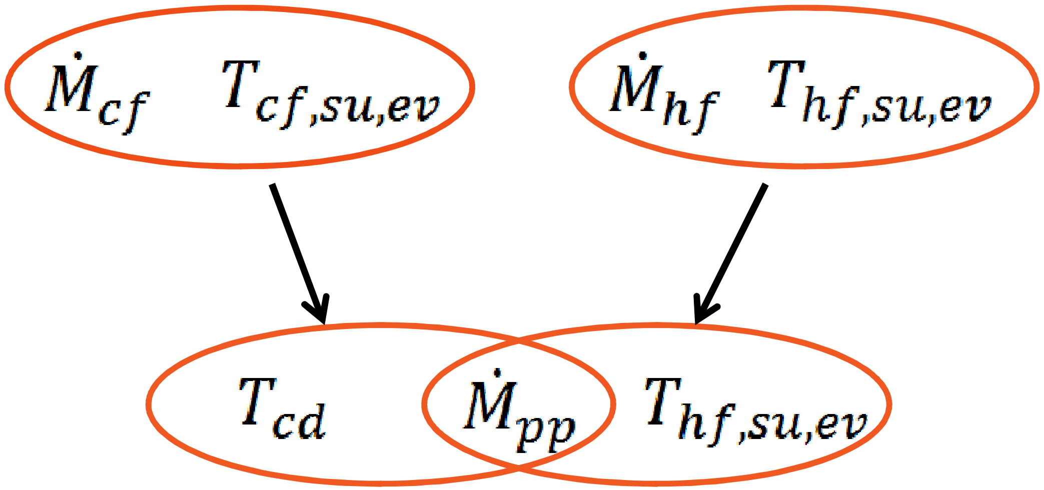


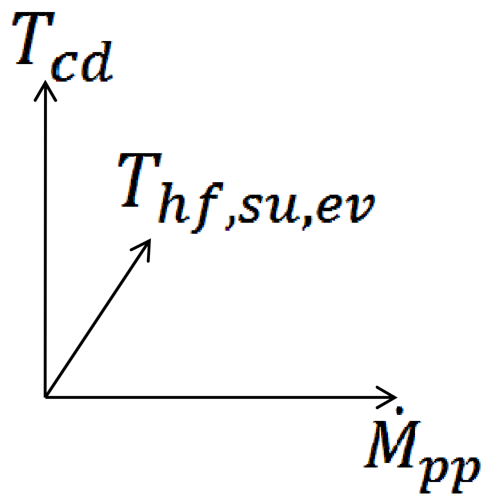
⚠ **No Recuperator!**

OPTIMAL EVAPORATION TEMPERATURE

Static optimization of the cycle

$T_{ev,optim}$ depends on the heat source/sink conditions:

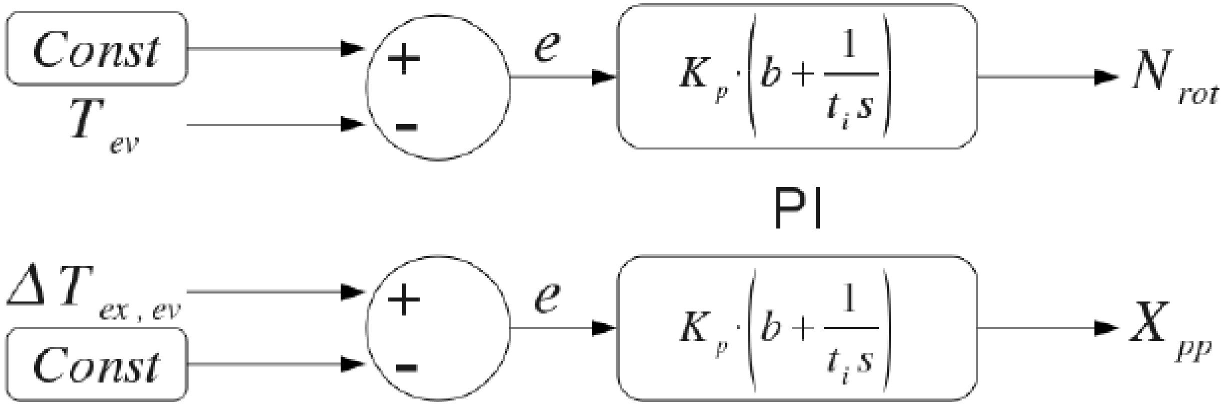


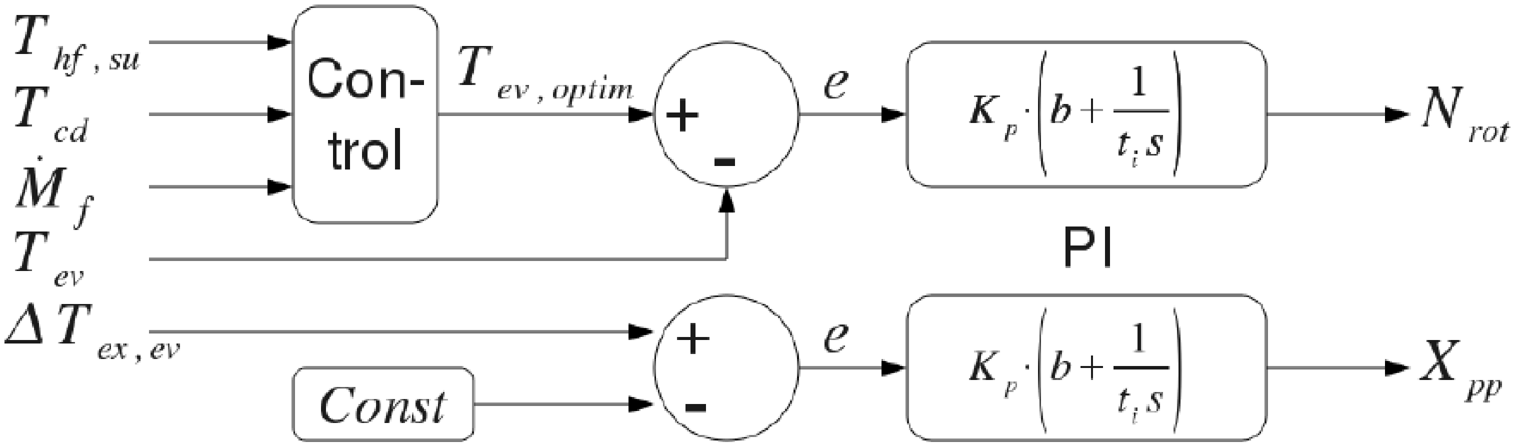


$$T_{ev,optim} = 77.6 + 4.93 \cdot 10^{-05} \cdot p_{cd} + 23.8 \cdot \ln(\dot{M}) + 7.65 \cdot \ln(T_{htf,su,ev})$$

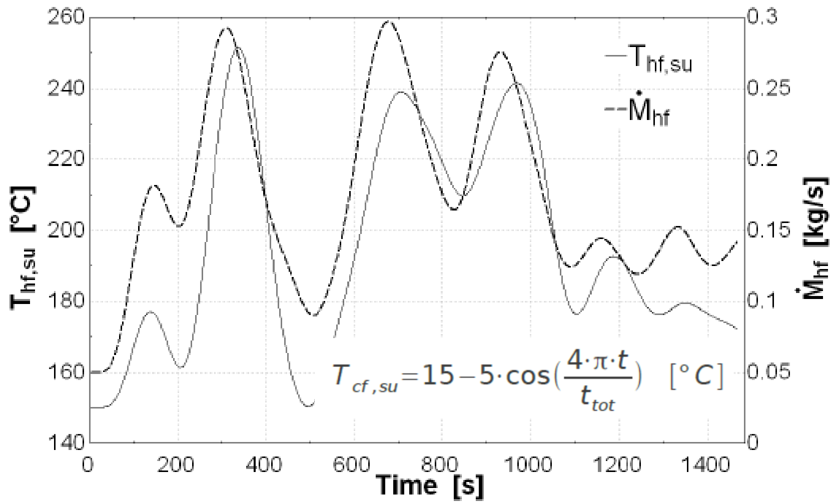
$$R^2 = 93.7\%$$

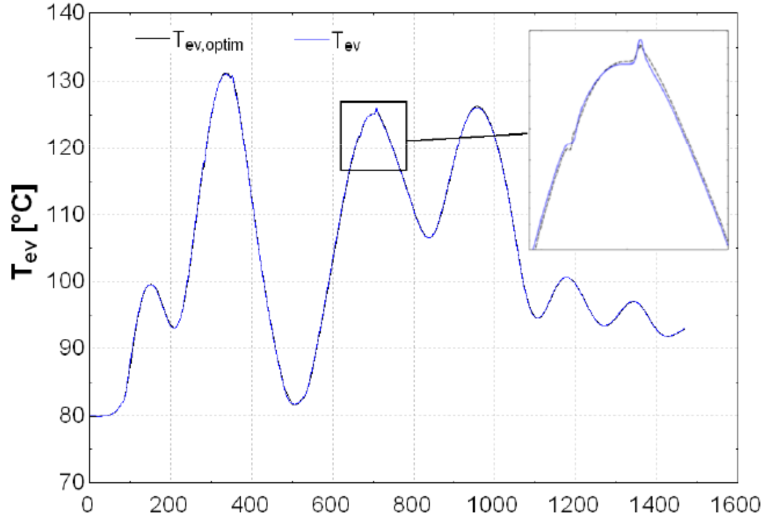
CYCLE FEEDBACK CONTROL STRATEGIES

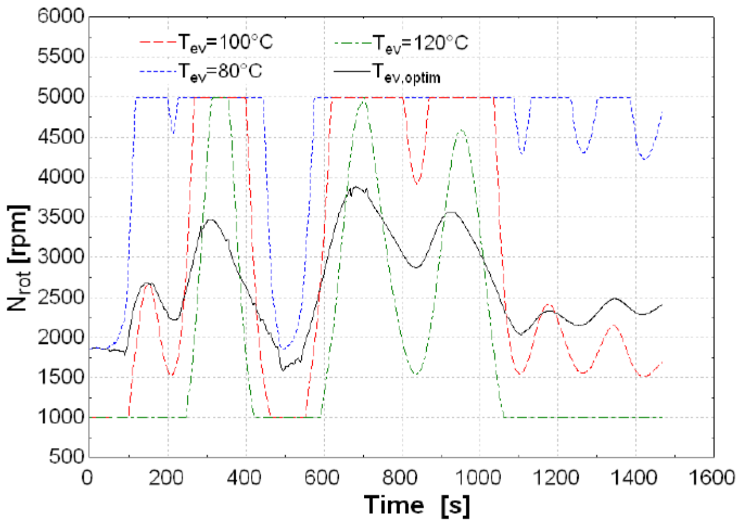


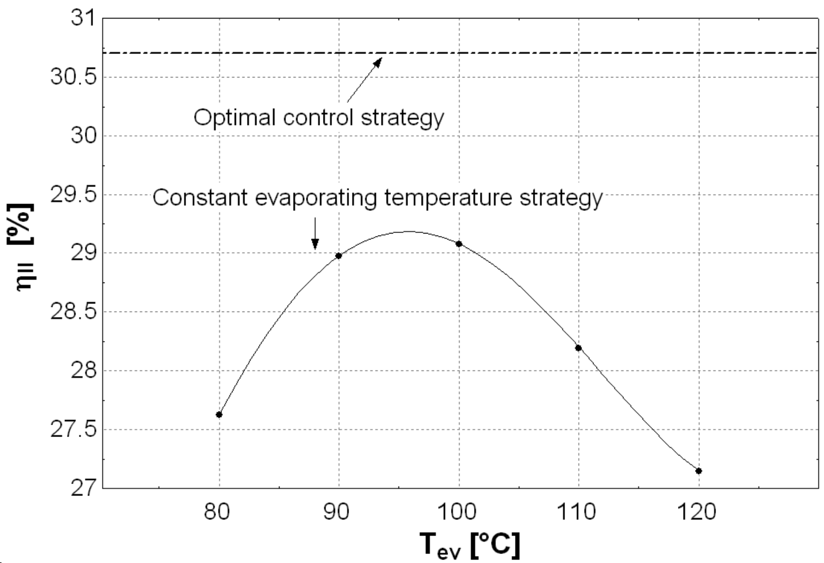


CYCLE FEEDBACK CONTROL STRATEGIES









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Model predictive control

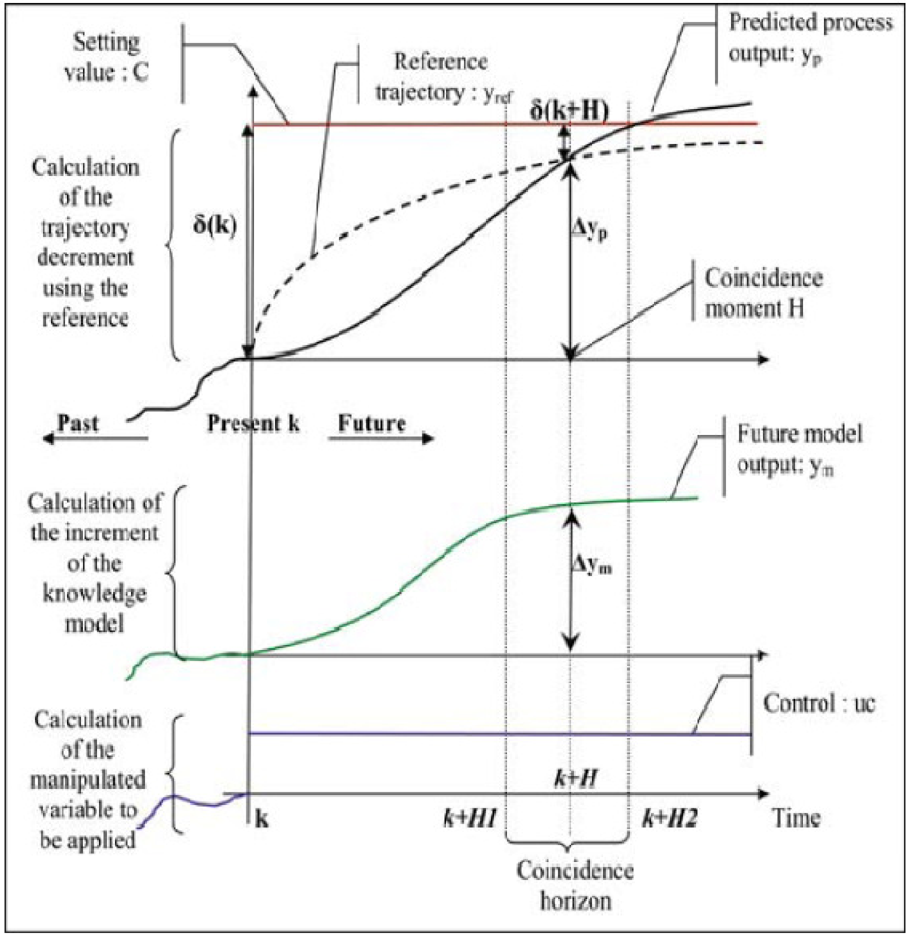
- ✓ Future action on the manipulated variable is based on a model.
- ✓ Balance between two different approaches:
  - model evaluation of the manipulated variable to reach the set point
  - Constant rectification of the trajectory by measurement of the control variable.
- ✓ Anticipates the effects of external perturbations
- ✓ Well-performing with constrained processes

Control unit

- ✓ First order model to predict the process:

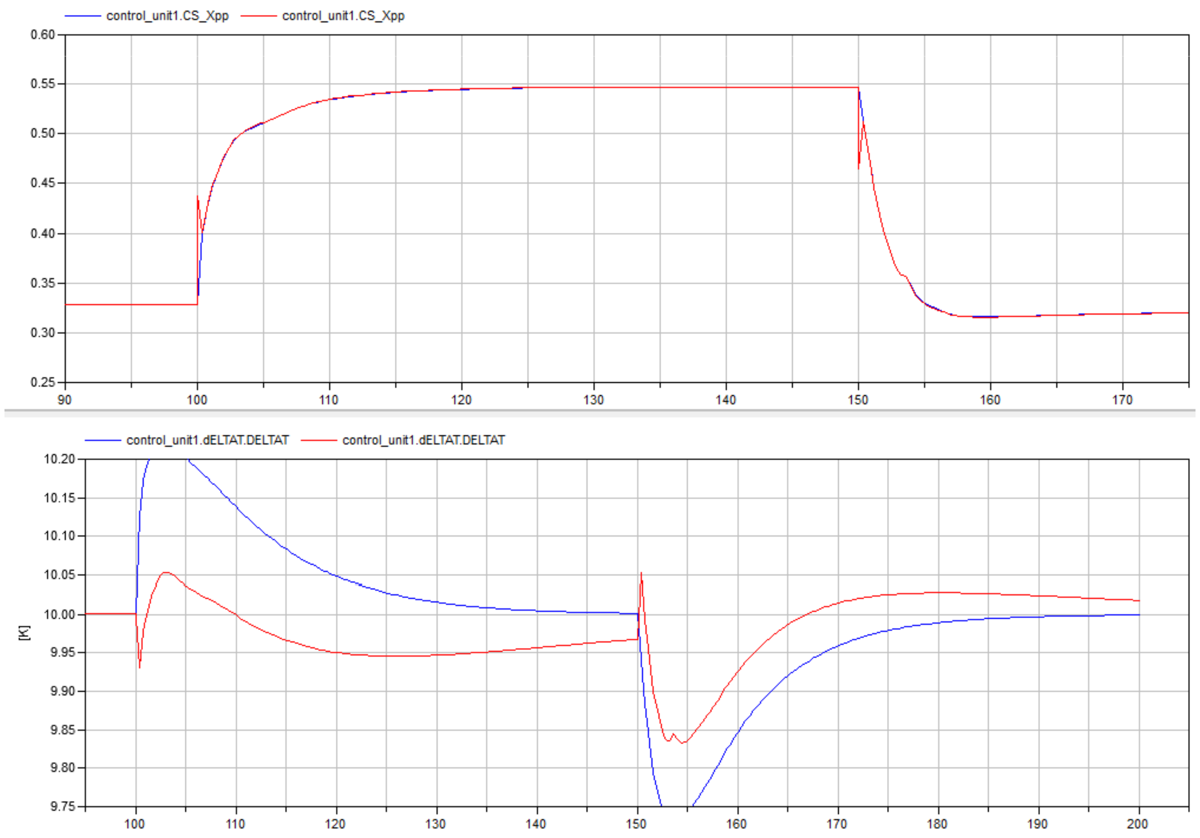
$$G(s) = \frac{\text{process output}}{\text{process input}} = \frac{K \cdot e^{-T_d s}}{1 + \tau \cdot s}$$

- ✓ Defined a desired trajectory to the set point
- ✓ Define an "horizon time" for which the model predicts an intersection between the desired trajectory and the process.

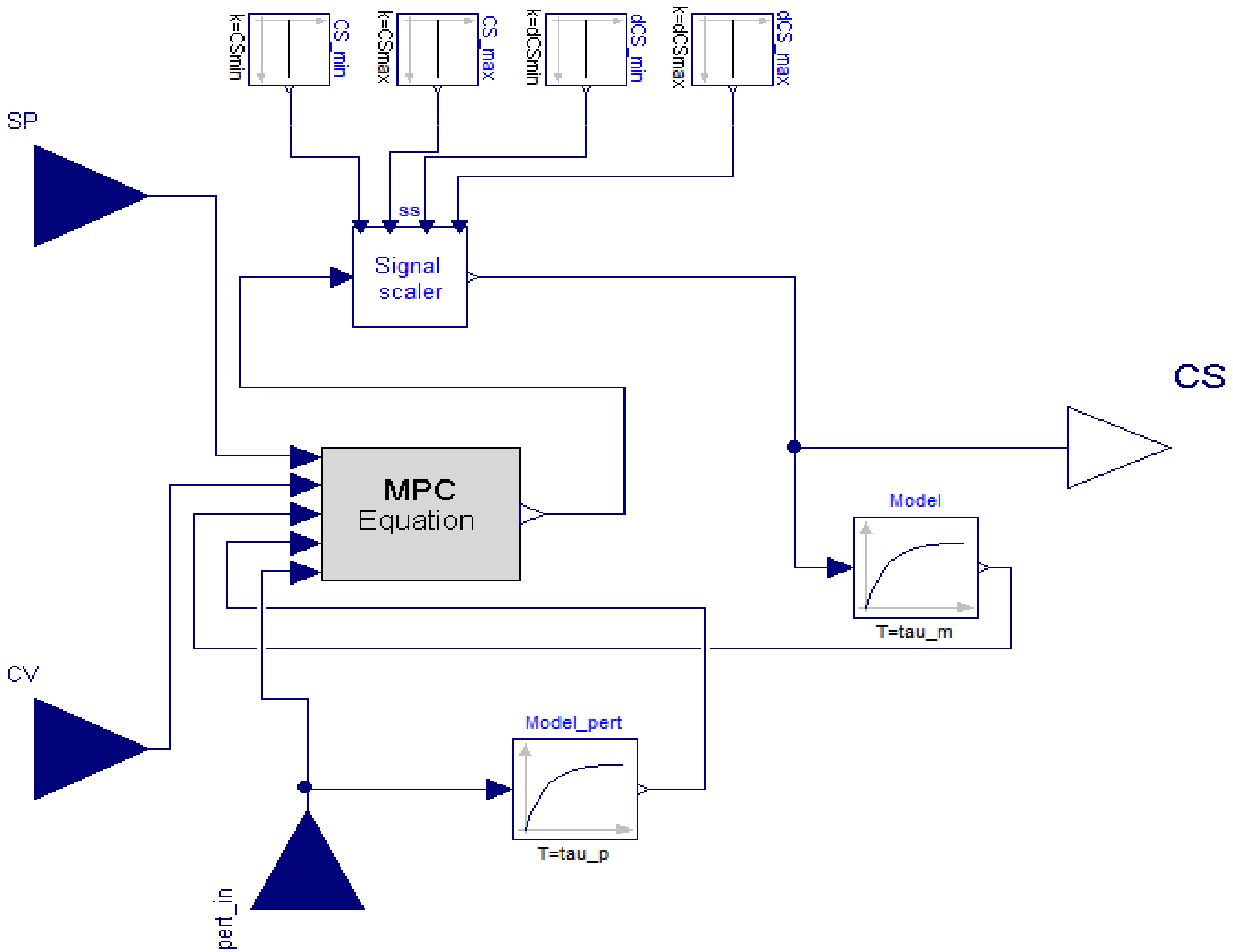


Accounting for measured pertubations

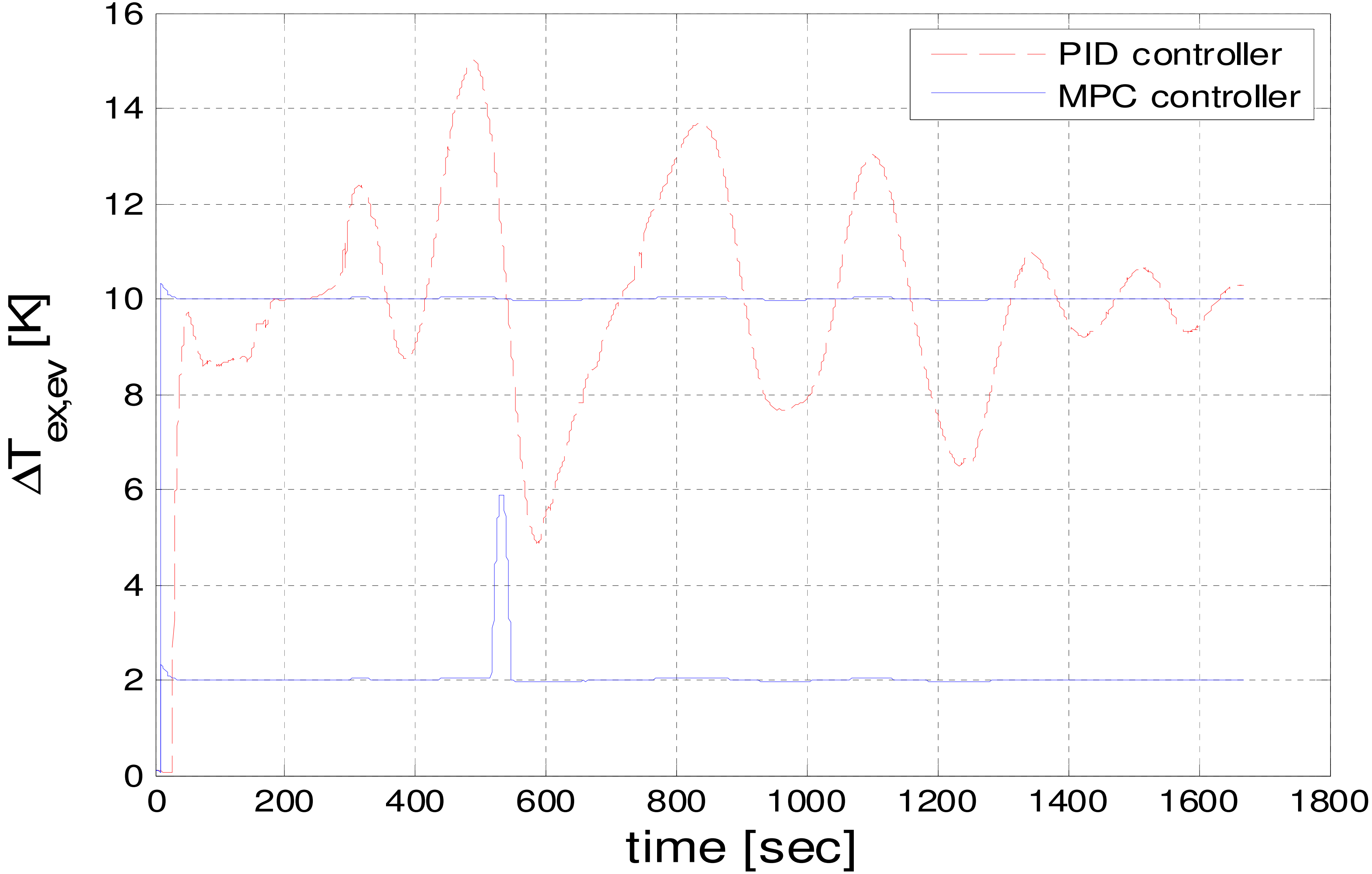
- ✓ The effect of an external pertubation is anticipated by the control.
- ✓ A first order model must be defined to account for these external influences.



Modelica implementation



Simulation results



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Summary

- ✓ A robust dynamic model of an ORC has been developed, based on validated steady-state component models
- ✓ Different control strategies have been proposed an compared
- ✓ A varying set-point control strategy allows increasing the output by more than 4%
- ✓ MPC controller follow the superheating set point in a much better way than PI-based controllers.
- ✓ Future work will focus on the implementation and the improvement of MPC controllers with delayed processes, during start & stop procedures and in more severe conditions.

Thank you!