4th International Seminar on ORC POWER SYSTEMS
ORC 2017
13 - 15 September
MILANO, Italy

Strategies for the optimization of a WHR ORC system

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Introduction: Small scale Waste Heat Recovery

Optimization of the system:

Working Fluid

System architecture

Expander and Heat Exchangers

Control and Management

Waste heat recovery system often characterized by fluctuations of mass flow rate and temperature;

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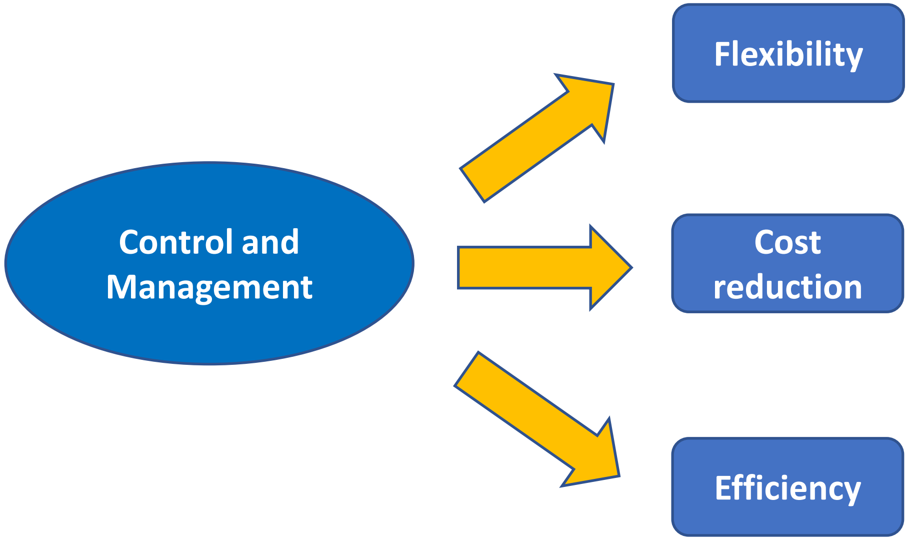
Introduction: Small scale Waste Heat Recovery



In the literature:

- Definition of control strategy (steady-state analysis);
- Definition of control strategy (transient-analysis)

General requirement:

- Easy measurable control variables;

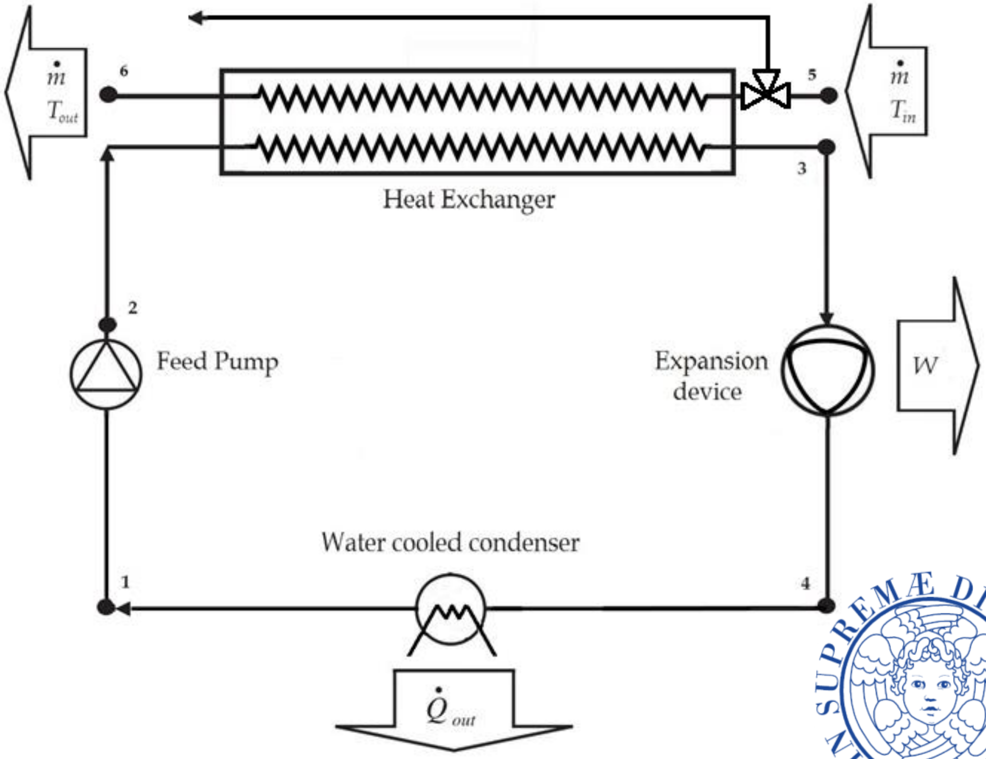
Aim of the work

Aim of the study:

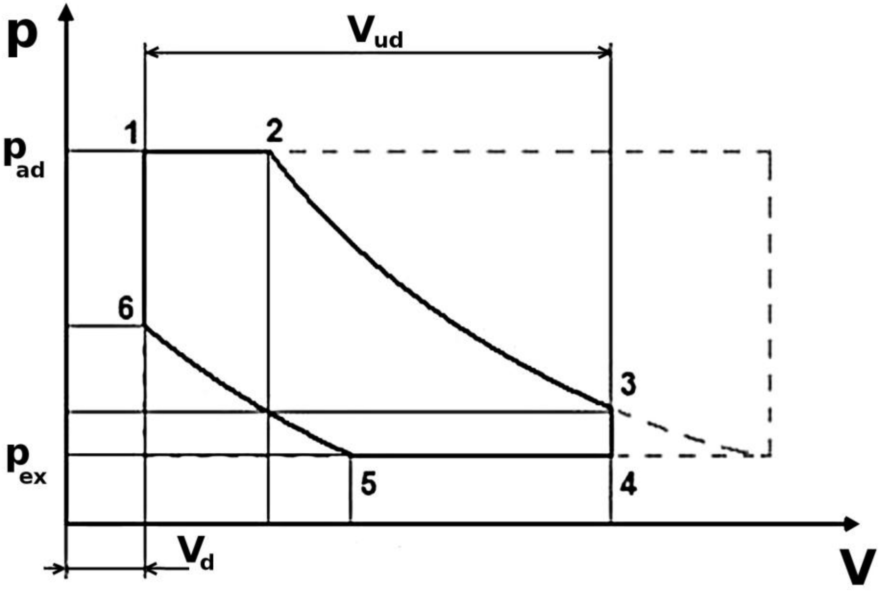
- Create a transient model of a small scale WHR-ORC;
- Compare various control strategies;
- Define an optimal control strategy;
- Define easy measurable control variables;

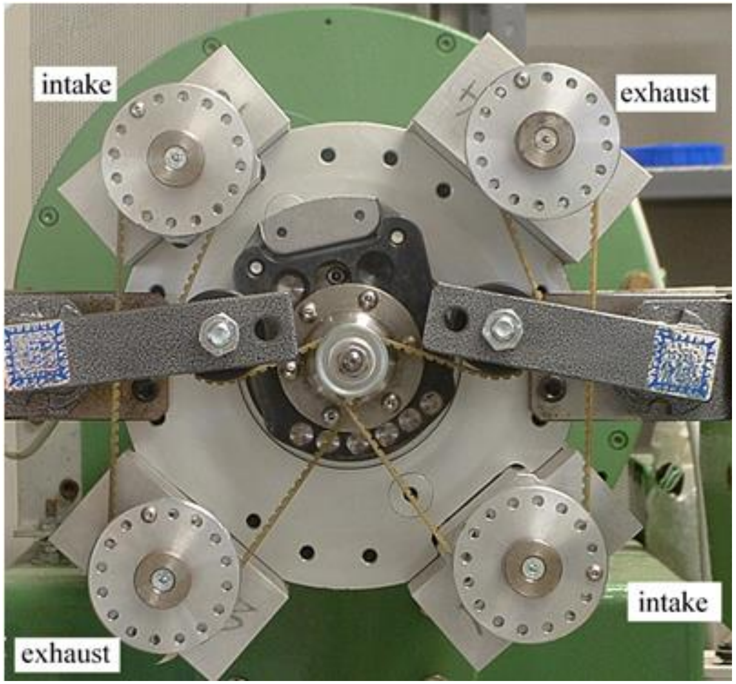
Methodology and System Layout

- Expander: rotary volumetric expander (from Wankel engine);
- Recovery from hot gas (T<200°C): direct exchange;
- By-pass valve of the evaporator;
- R-600a: Working Fluid;
- FWH modality;



Methodology: Expander





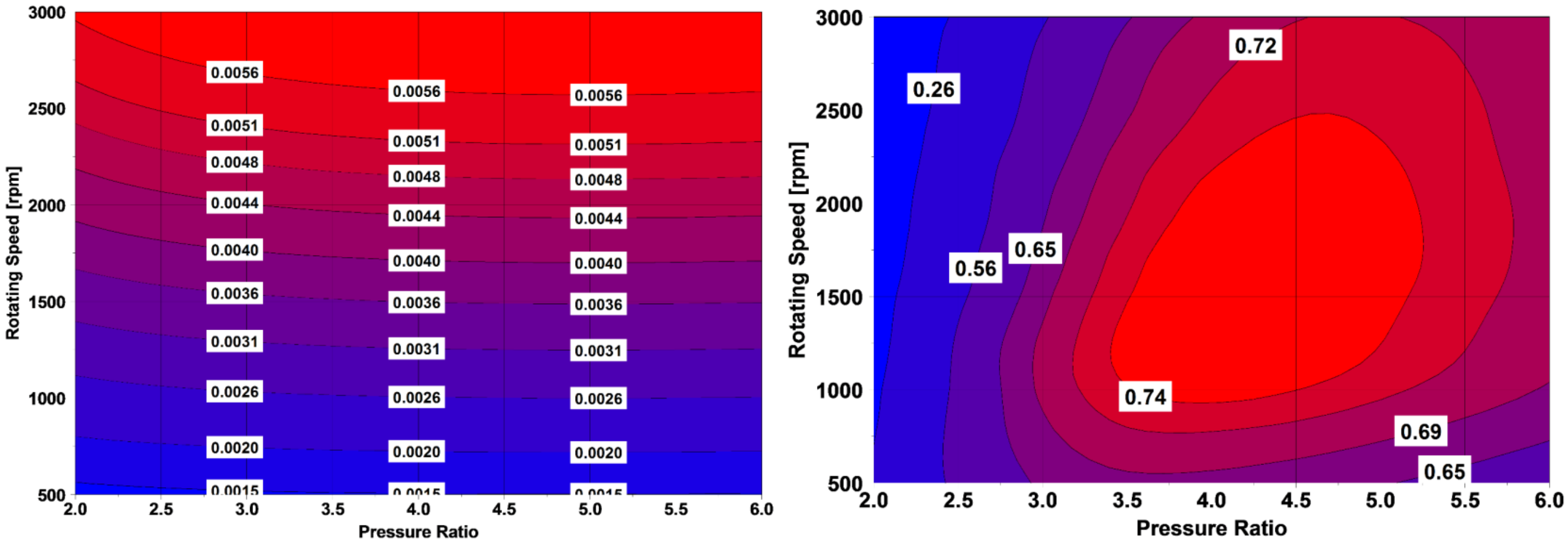
Main driving parameters:

- Displacement: 316cc
- Dead space grade $\mu = V_1/(V_3\text{-}V_1) = 8\%$
- Introduction grade $\sigma = (V_2\text{-}V_1)/ (V_3\text{-}V_1) = 20\%$
- Expansion grade $\varepsilon = V3/V2; = 3.86$
- Recompression grade $\gamma = (V_5\text{-}V_6)/(V_3\text{-}V_1) = 10\%$

Methodology: Numerical Model

Numerical model realized in AMESim

Expander maps from a numerical model validated with experimental data



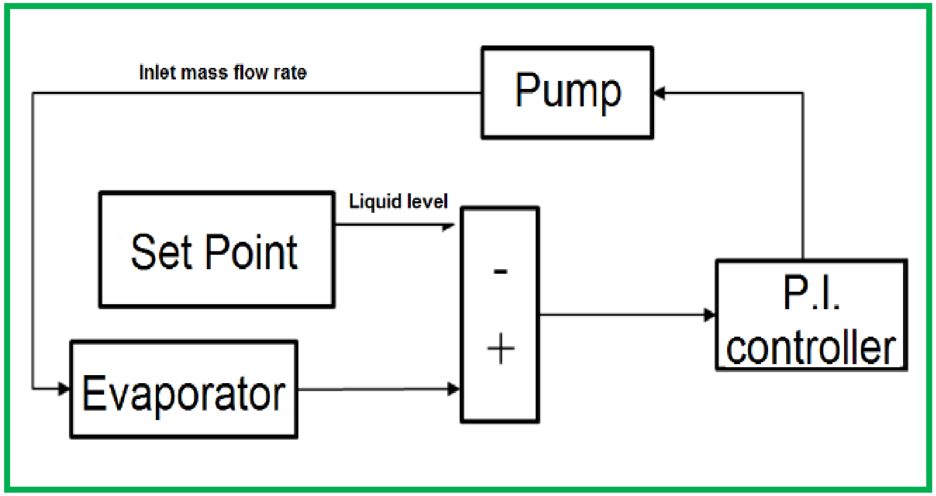
Evaporator: discretized in various nodes (finite volume).
Heat exchange coefficient determined directly evaluated by the code (built-in correlations).
Condenser: simplified model (two-phase chamber with imposed temperature)

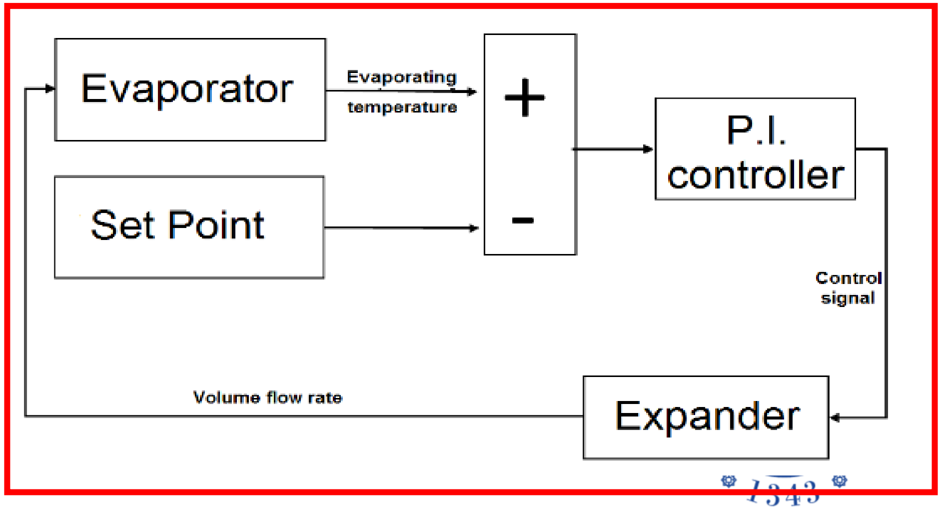
Methodology: Control strategy and control system

Control strategy:

- Sliding-Pressure (constant expander speed);
- Sliding-Velocity (constant evaporating. Temperature): inverter required;
- Combined: inverter required;

Control Loops:





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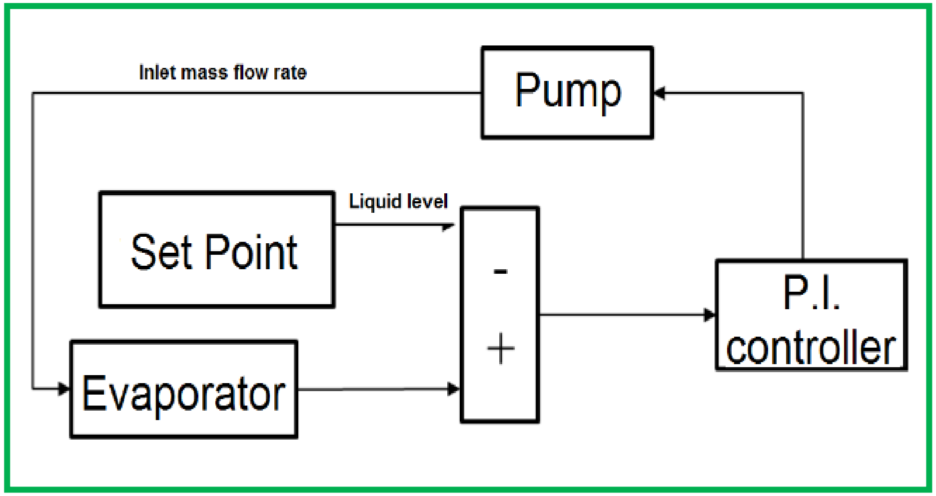
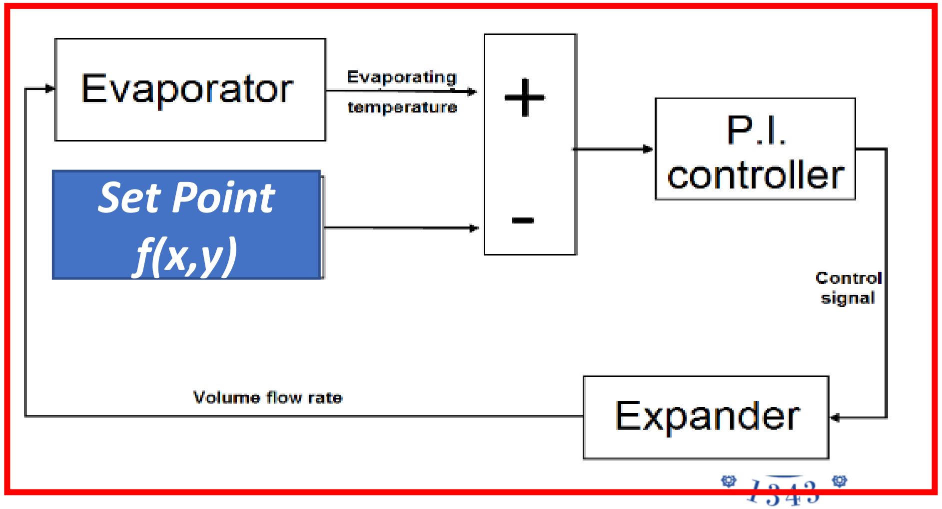
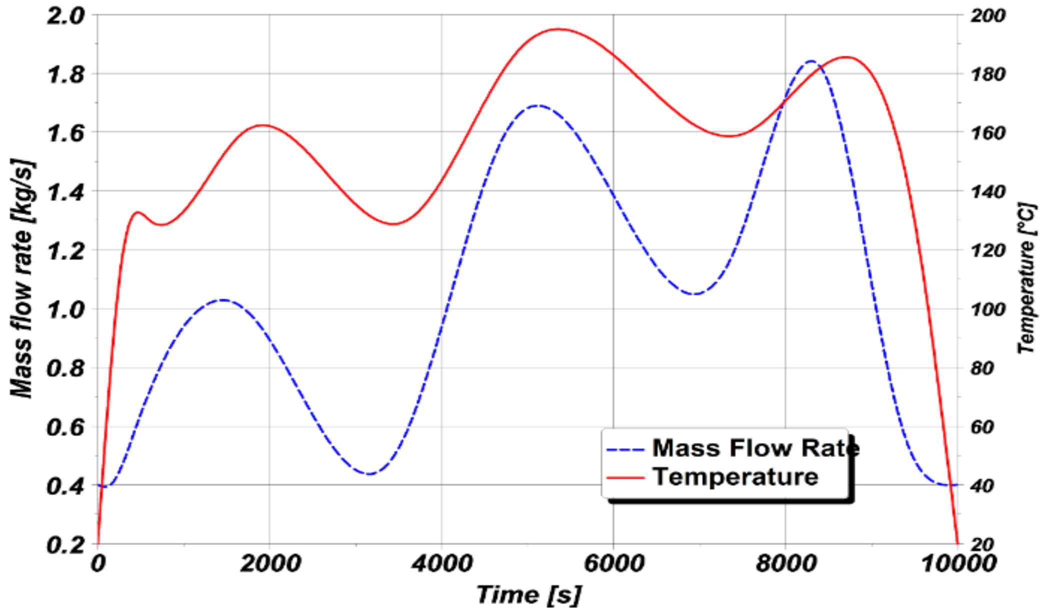




Methodology: Boundary Conditions

Load diagram defined by variations both of temperature and mass flow rate

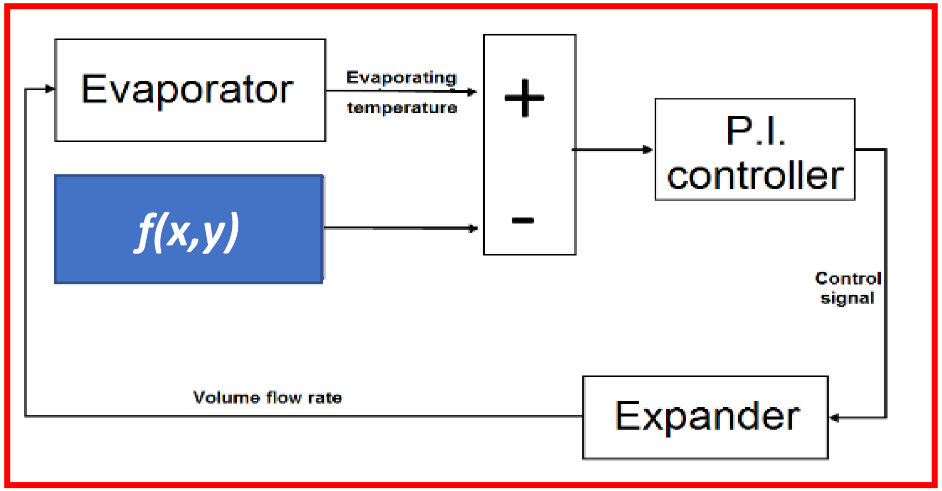


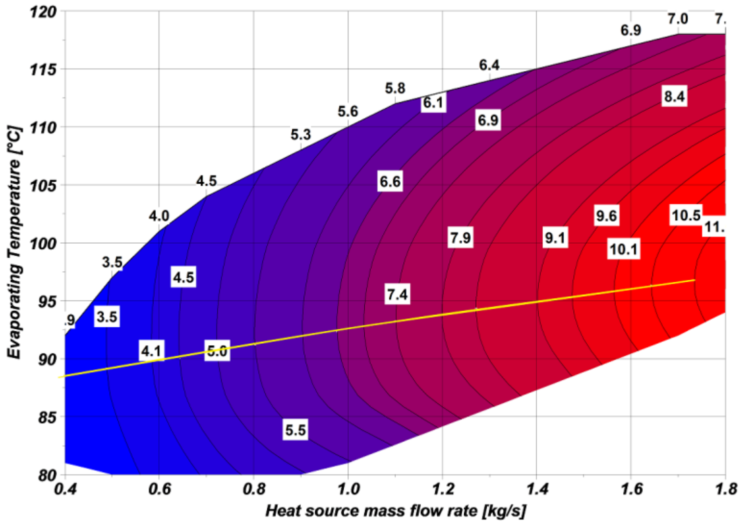
Simplification: constant condensing temperature (35°C).

Methodology: Combined Strategy

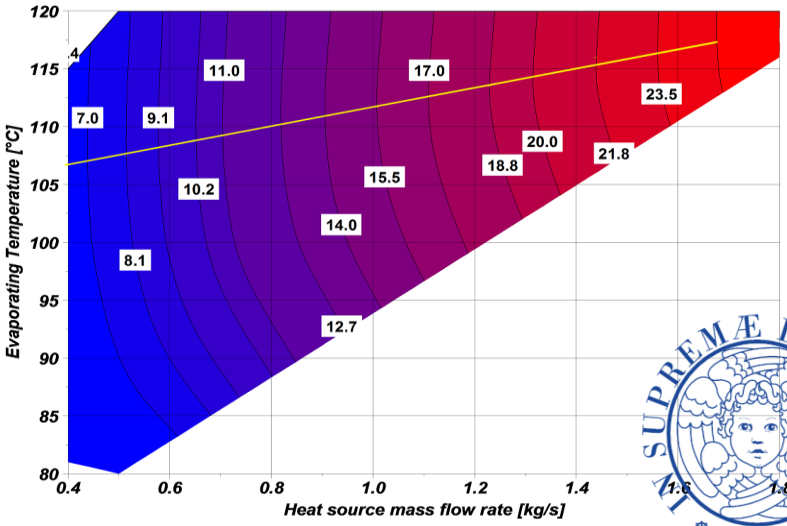
A function of at least two variables (three if condensing temperature is not constant) is required;

Function evaluated from system simulation in steady-state conditions, by maximizing the work output;





Heat source temperature =130°C



Heat source temperature =180°C

Methodology: Combined Strategy

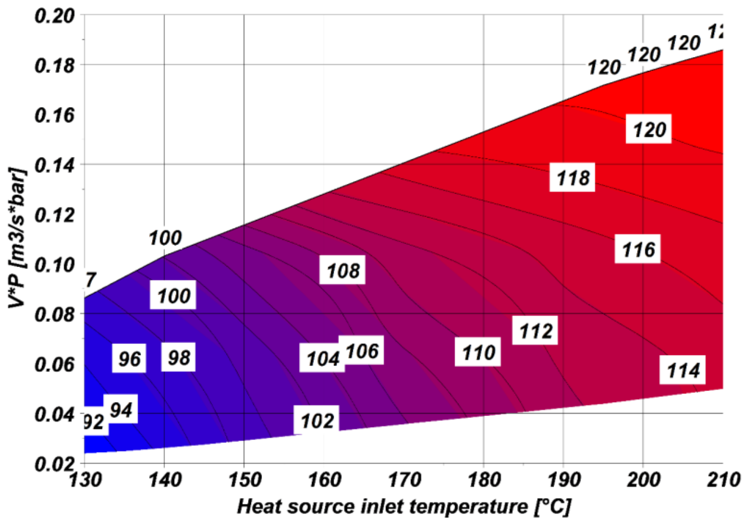
General issue: the heat source mass flow rate can be hardly measurable;

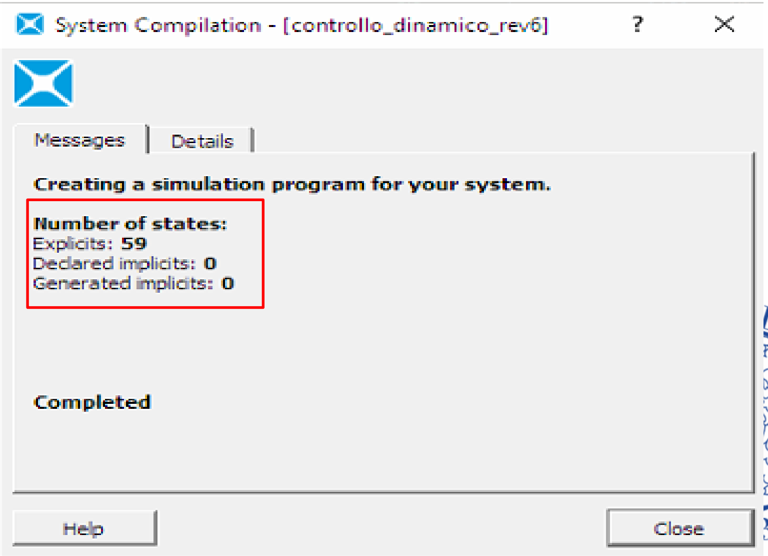
A different quantity might be more suitable to drive the evaporating temperature;

The product $\dot{V} \cdot \Delta P_{EXP}$ related to the expander work output and univocally defined;

For constant condensing temperature, the function became $\dot{V} \cdot P_{Adm}$: due to pressure drop $P_{Adm} \neq P_{Sat}$

Explicit solution of the control loop



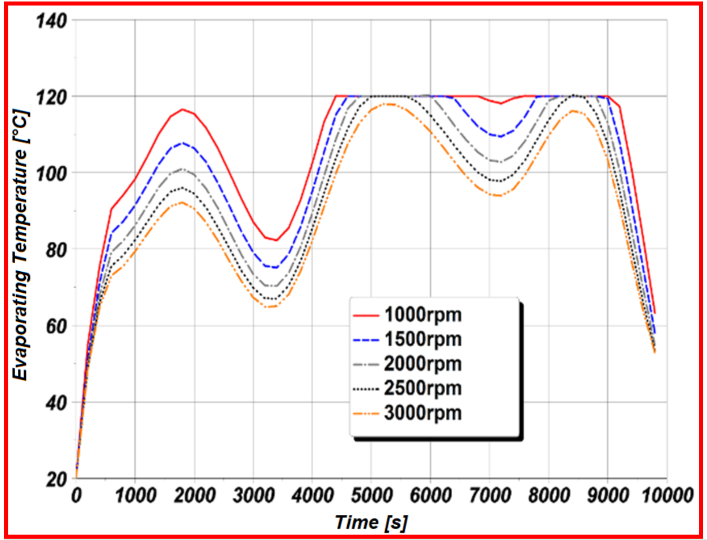


Creating a simulation program for your system.

Number of states:
Explicits: 59
Declared implicits: 0
Generated implicits: 0

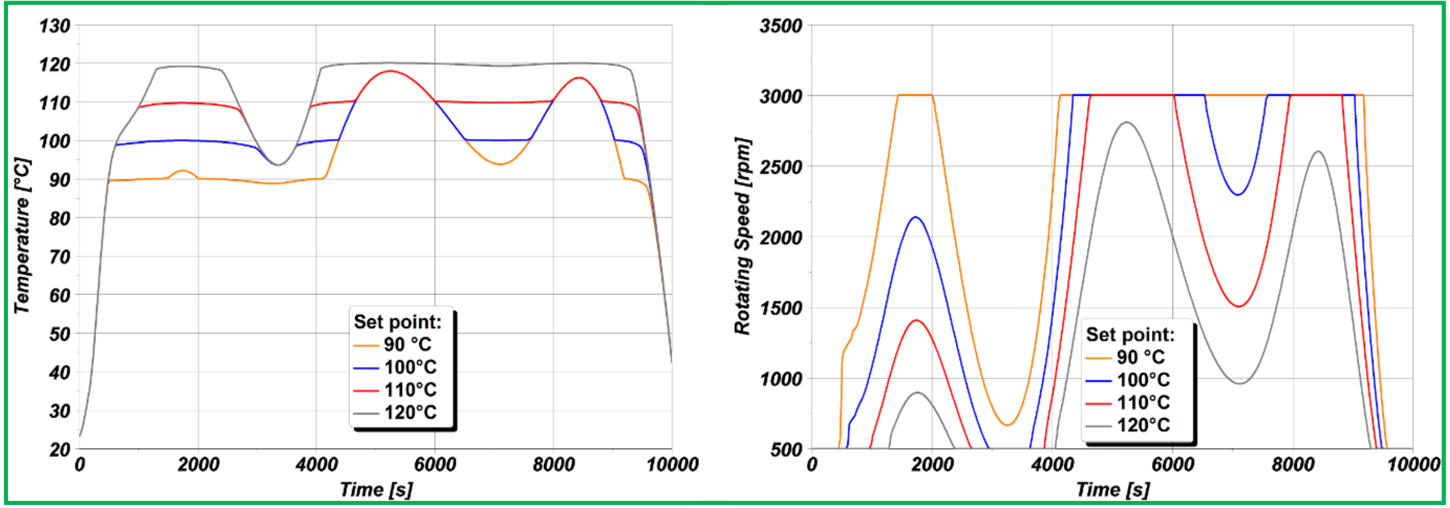
Completed

Results: Sliding Pressure/Sliding Velocity



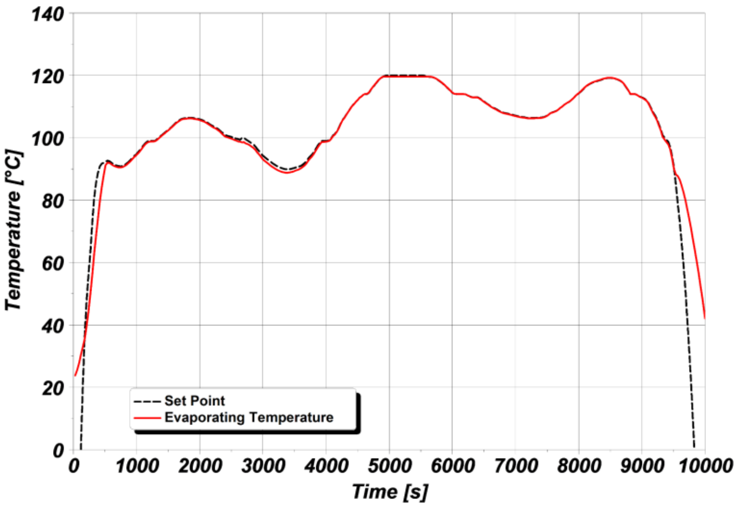
		Sliding Pressure [2500 rpm]	Sliding Velocity [T_{ev}=100°C]
Average Net Output	[kW]	**9.77**	**9.81**
Average ORC Efficiency	[%]	**10.51**	**11.73**
Average Recovery Efficiency	[%]	**60.46**	**54.41**
Average Overall Efficiency	**[%]**	**6.35**	**6.38**

Sliding Pressure: variation of evaporating temperature

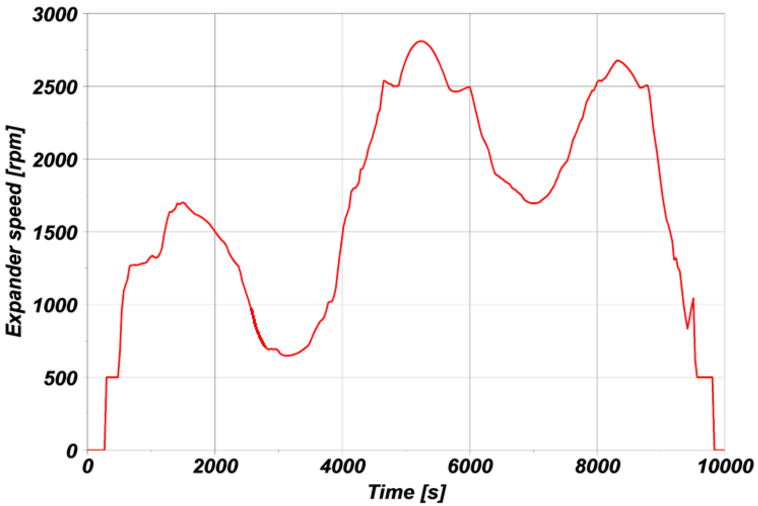


Sliding Velocity: evaporating temperature and exp. speed

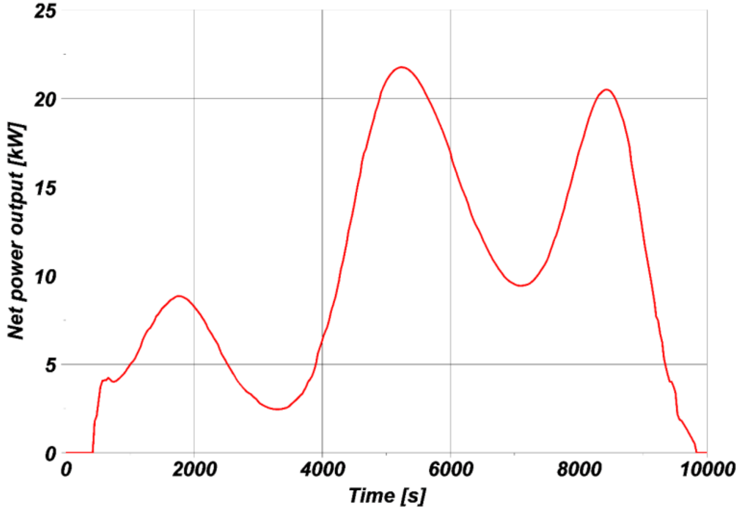
Results: Combined strategy



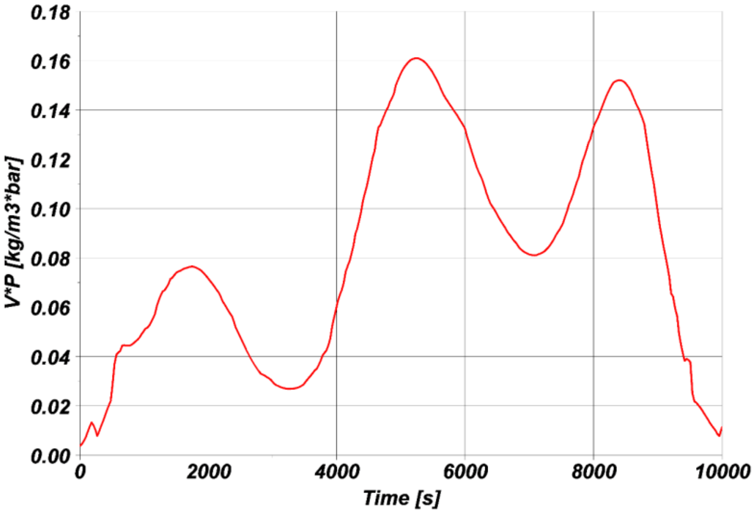
Evaporating temperature



Expander Speed



Net Power Output



$V \cdot \dot{P}_{adm}$

Results: Comparison of the strategies

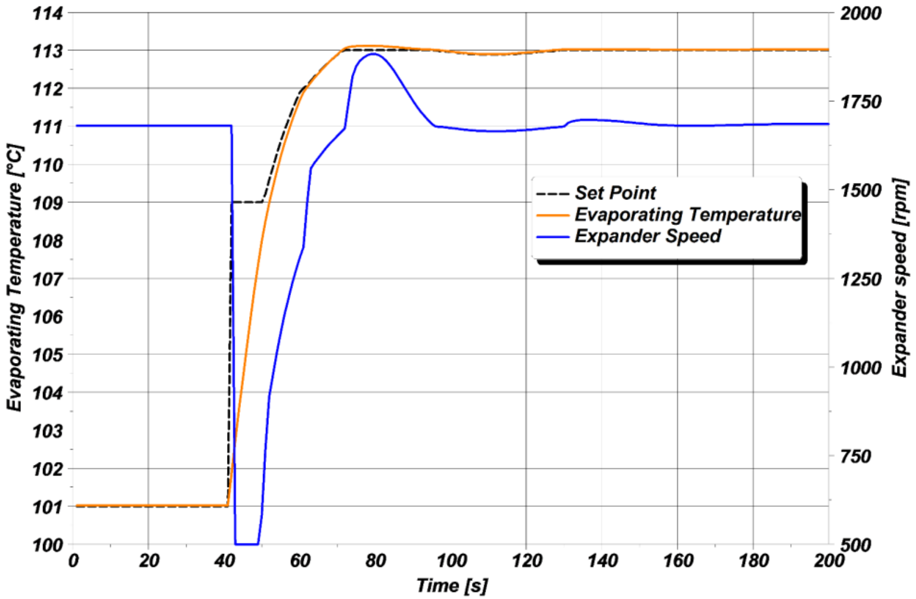
		Sliding Pressure [2500 rpm]	Sliding Velocity [T_{ev}=100°C]	Combined
Average Net Output	[kW]	**9.77**	**9.81**	**9.93**
Average ORC Efficiency	[%]	**10.51**	**11.73**	**9.92**
Average Recovery Efficiency	[%]	**60.46**	**54.41**	**65.11**
Average Overall Efficiency	**[%]**	**6.35**	**6.38**	**6.46**

Combined strategy did not required to determine a-priori an optimal value of sliding pressure and sliding velocity;

The value of the work output however is not so much higher than that of the two other strategies: dynamic effects.

Results: Step Response

Temperature of the heat source increased from 150°C to 180°C at t=40s



Due to system inertia the evaporating temperature did not manage perfectly following the set point;

The optimal value of the set point in transient conditions differs from steady-state

A dynamic optimization of the system is required to achieve better results.

Conclusion

- Control strategies for WHR ORC have been pointed out;
- An optimization has been carried out;
- A new control variable $\dot{V} \cdot \Delta P_{EXP}$ has been tested to drive the evaporating temperature of the ORC;
- For each temperature and mass flow rate of the heat source the variable is univocally defined and easily measurable;
- The control loop was explicitly solved.
- The set point driving function was defined in steady-state conditions;

Further developments

- Experimental tests are needed to verify the actual feasibilty of this choice.

Possible problems:

- The small entity of the pressure drop;
- Noise in the pressure values;

Thank you!