LABORATOIRE DE THERMODYNAMIQUE UNIVERSITE DE LIEGE

PSA GROUPE

DIRECTION RECHERCHE ET DEVELOPPEMENT

# DESIGN OPTIMIZATION OF RANKINE CYCLE SYSTEMS FOR WASTE HEAT RECOVERY FROM PASSENGER CAR ENGINES

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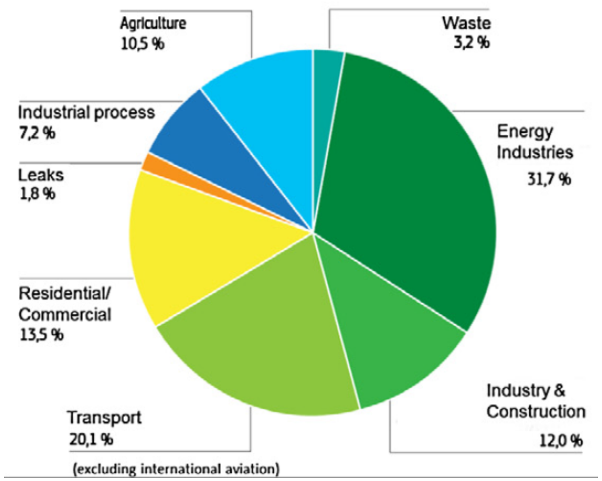
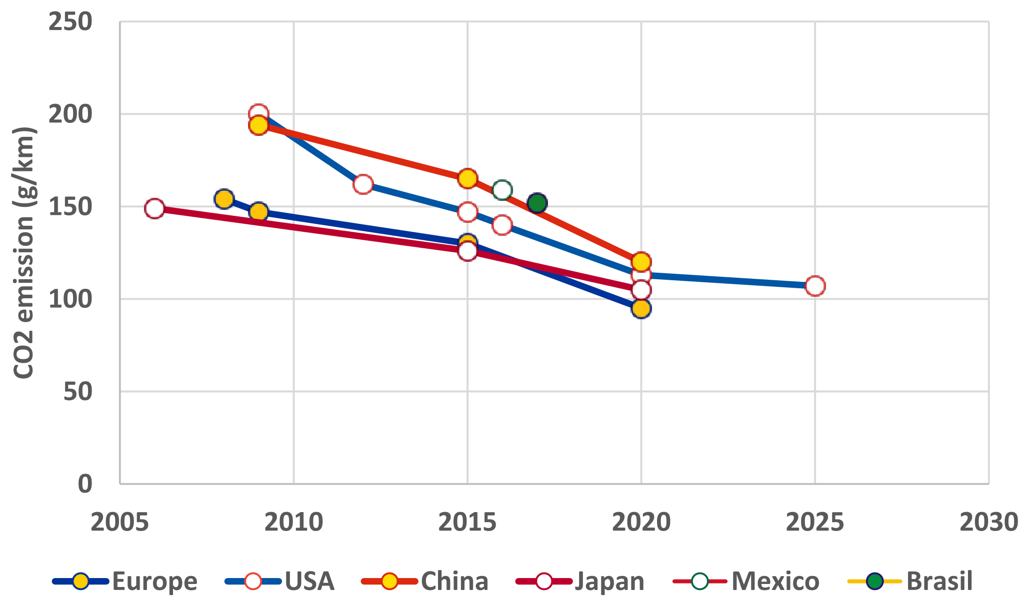
# Introduction

## *Context*




- Transportation represents a significant part of world energy consumption and $CO_2$ emissions.

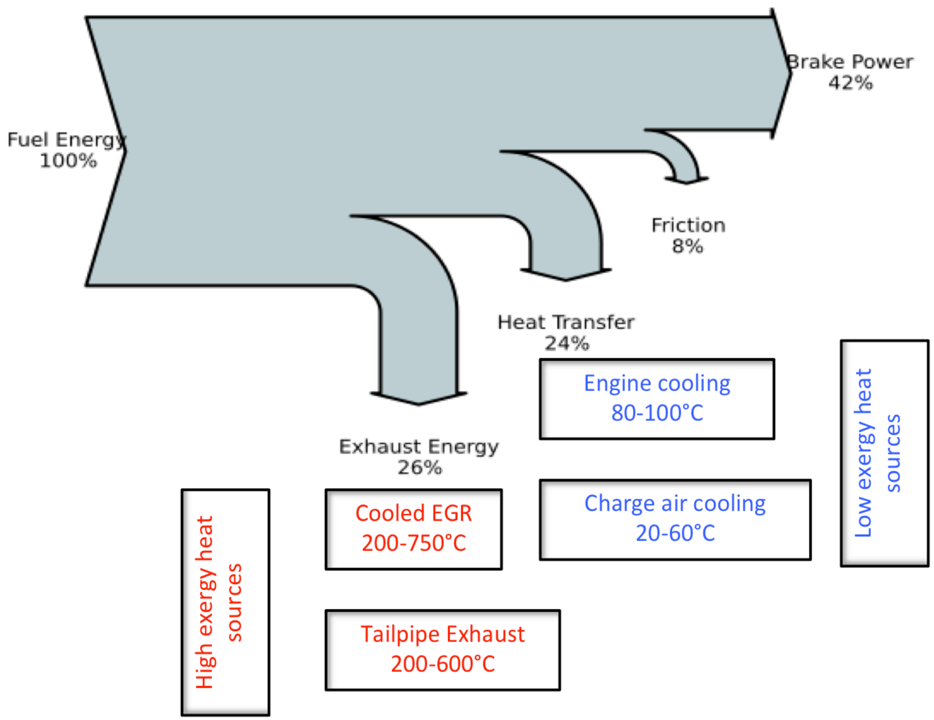



- Worldwide regulations enforce to decrease the $CO_2$ emissions of passenger cars
- Increasing the efficiency of ICE is one of the mid-term strategies

# Introduction

## *Context*

*Combustion engine global efficiency can be increased by valorizing waste heat*



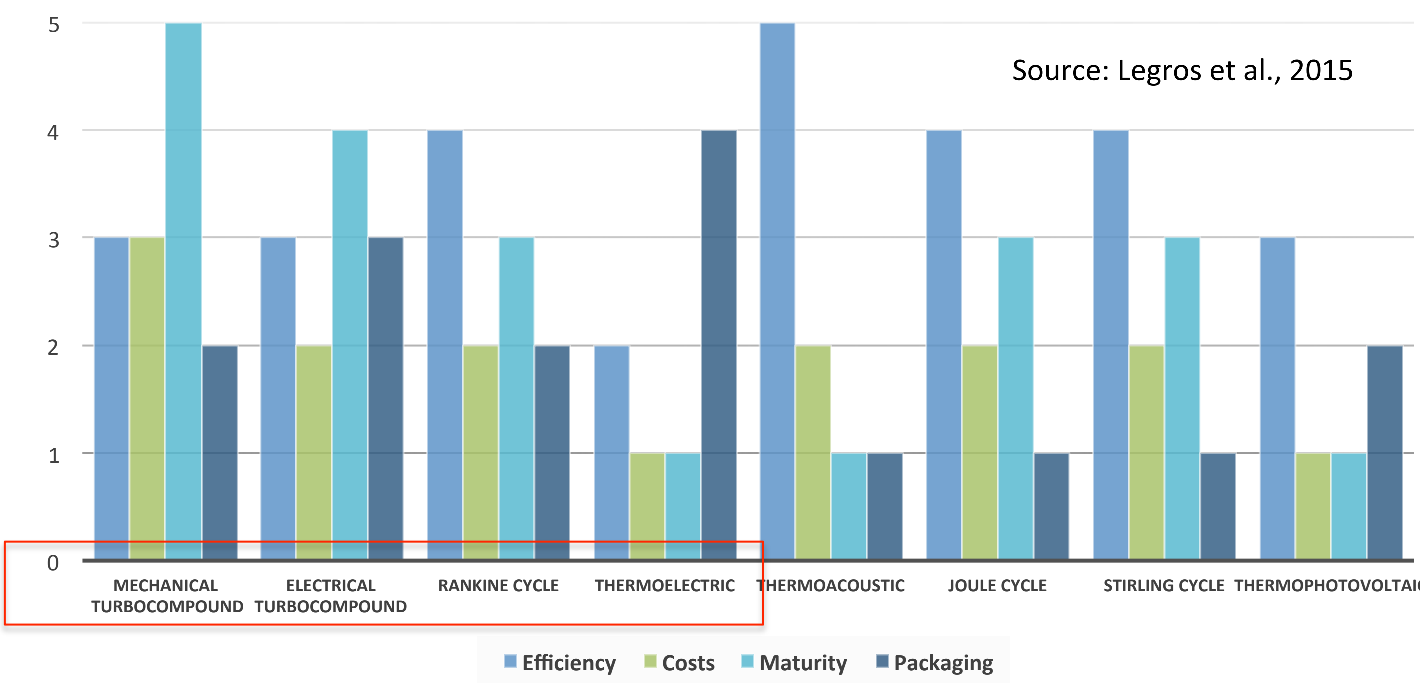

- Almost 2/3 of fuel energy is lost in exhaust heat and engine cooling circuit
- Waste heat sources differ by the amount and quality of energy available.
- There exists different techniques of waste heat recovery
  - To **produce power**
  - To produce cooling effect
  - To produce heating effect

# *Content of the presentation*

1. Introduction
2. **Comparison of waste heat recovery techniques for passenger cars**
3. Design of a scroll expander
4. Tests on a prototype of components
5. Conclusions and perspectives

# WASTE HEAT RECOVERY TECHNIQUES

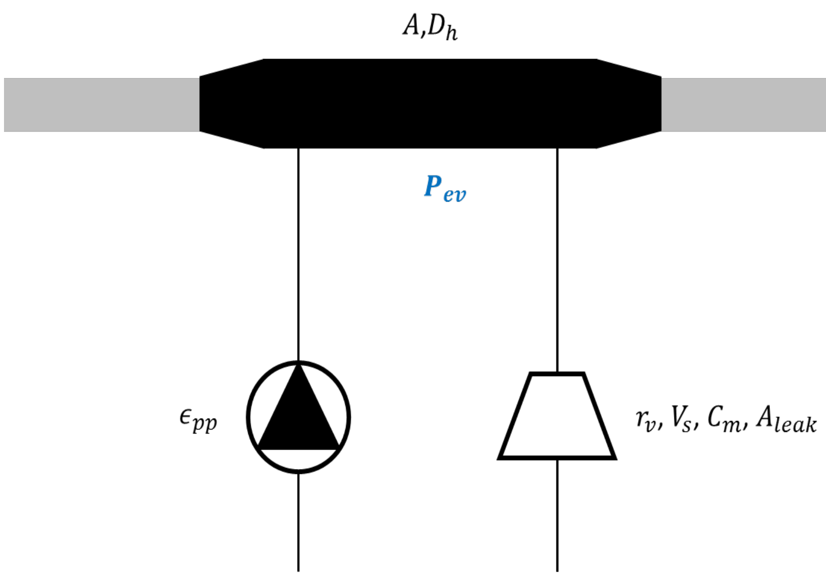
*Comparison based on litterature*

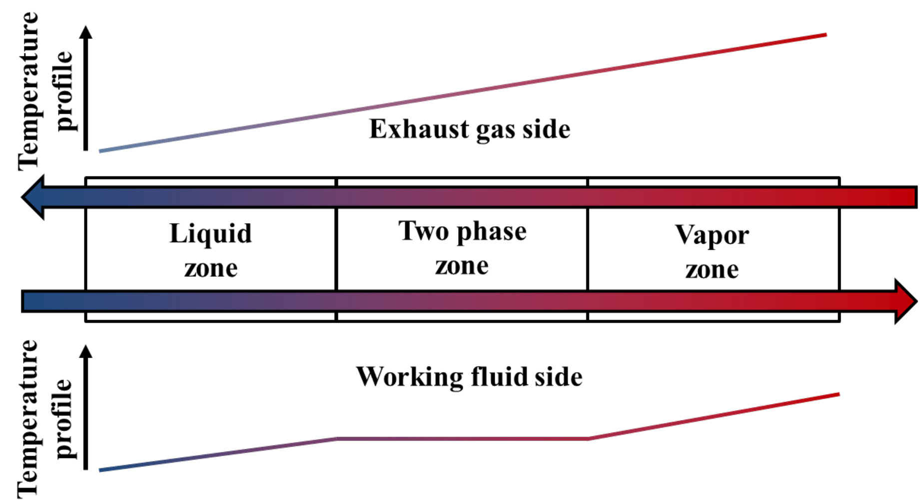



- Focus on **power production** (other technologies available for cooling: ejector, sorption)
- **Turbocompounding** and **Rankine** cycle are the most promising technologies
- **TEG**: lower produced power and low maturity
- Thermo-acoustics/thermo PV: low maturity
- Joule/Stirling cycle: large volume

# WASTE HEAT RECOVERY TECHNIQUES

*Comparison based on simulation – Rankine cycle model*

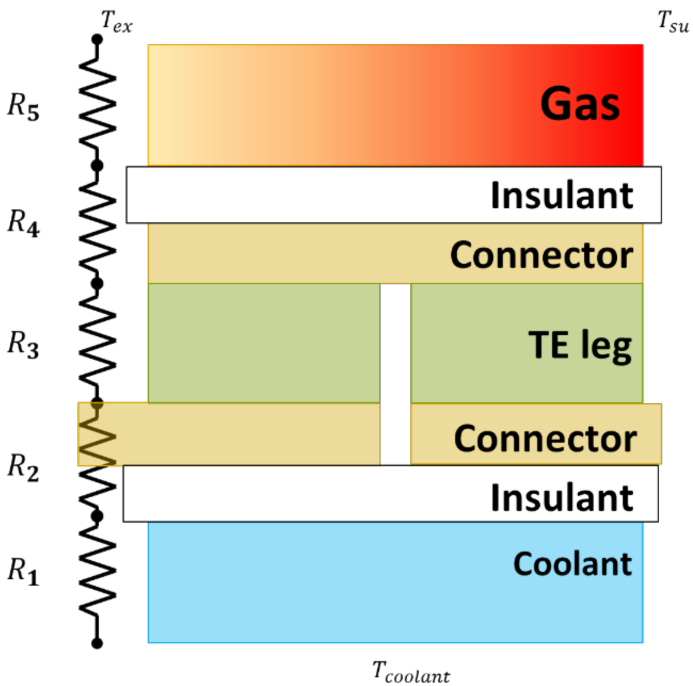



- 3-zone evaporator model
- Models calibrated based on experimental data
- Condenser not modeled since condensing temperature is maintained constant by control

# WASTE HEAT RECOVERY TECHNIQUES

## *Comparison based on simulation – TEG and TC models*



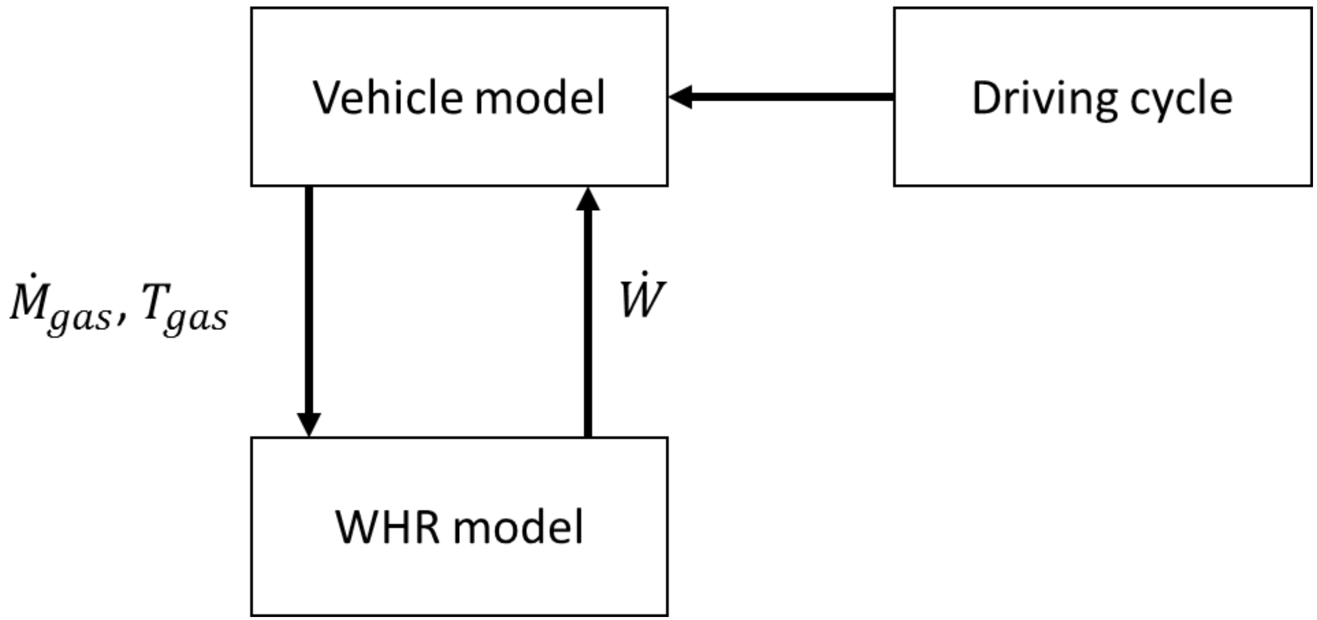

- Thermal resistances network
- TEG efficiency function of the figure of merit *ZT*.

$$\eta = \frac{\sqrt{1+\overline{ZT}}-1}{\sqrt{1+\overline{ZT}}+\frac{T_{cold}}{T_{hot}}}\frac{T_{hot}-T_{cold}}{T_{hot}}$$

- Regression model for the turbine efficiency and displaced mass flow rate
- Model parameters identified based on a turbocharger turbine

# WASTE HEAT RECOVERY TECHNIQUES

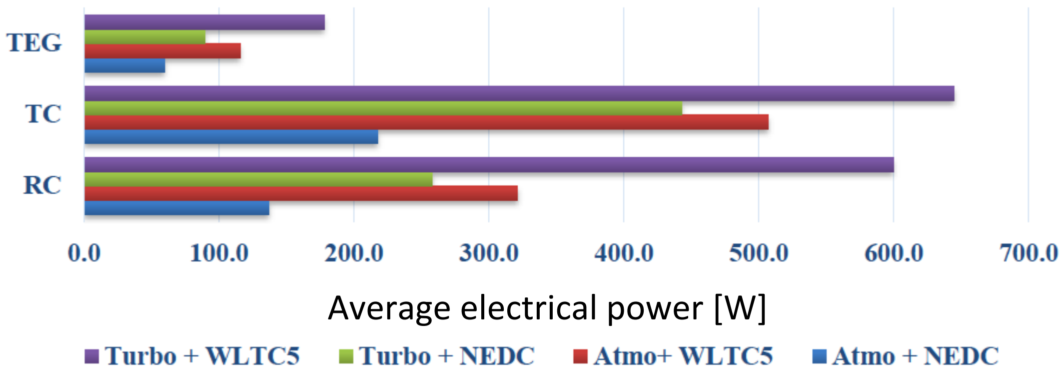
*Comparison based on simulation*



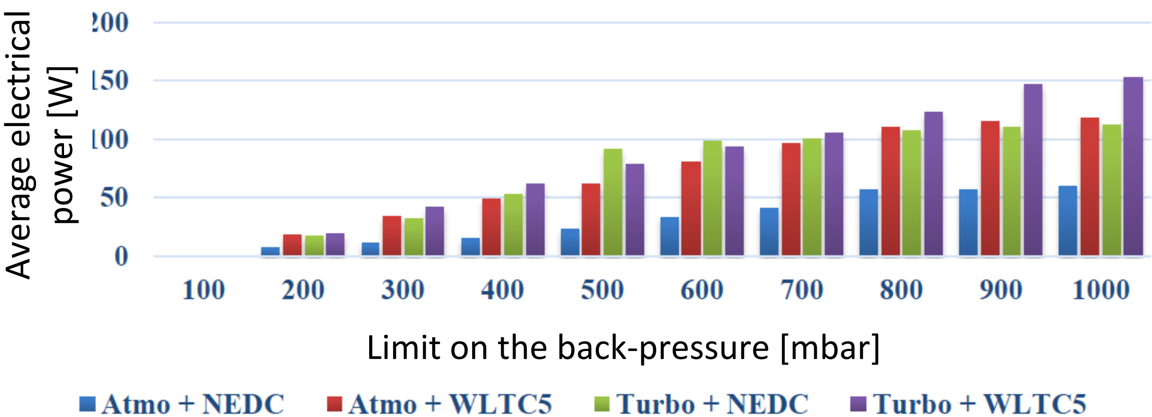

- WHR systems models are connected to a vehicle model
- Additional weight is taken into account
- Back-pressure not considered
- Power output is used to drive an electrical motor to boost the ICE

# WASTE HEAT RECOVERY TECHNIQUES

*Comparison based on simulation*



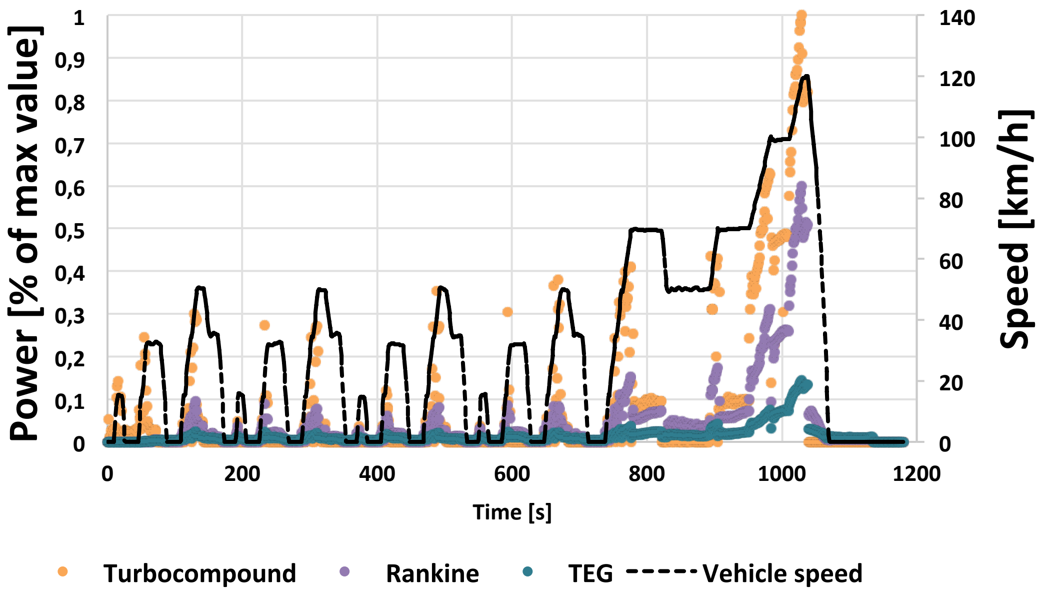

- Turbocompound yields the best results if engine back-pressure not taken into account




- Introducing a limit on the back-pressure sharply decreases the turbocompound power.

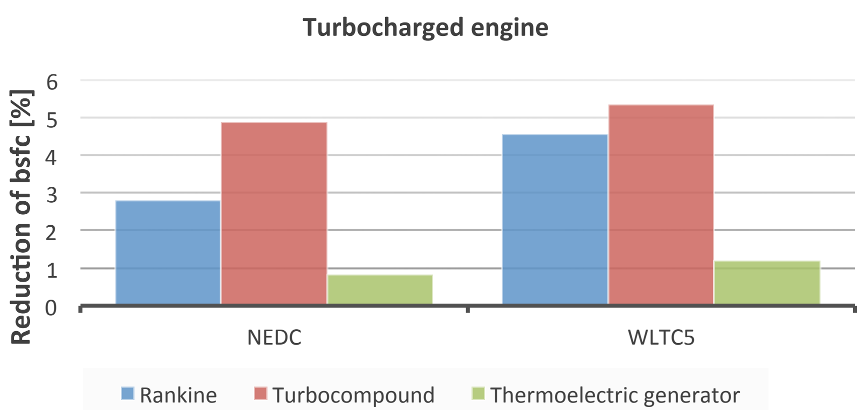
# WASTE HEAT RECOVERY TECHNIQUES

*Comparison based on simulation*




- TC: largest power, less frequent time of use (mainly accelaration phases), highly sensitive to mass flow rate
- RC more often used (except during start up), mid power
- TEG: lower power, almost awlways used, less sensitive to mass flow rate.

- Turbocompound yields the largest BSFC reduction if engine back-pressure not taken into account
- RC shows less back pressure (depending on the evaporator hydraulic performance) => good compromise.



# *Content of the presentation*

1. Introduction
2. Comparison of waste heat recovery techniques for passenger cars
3. **Design of a scroll expander for a Rankine cycle system**
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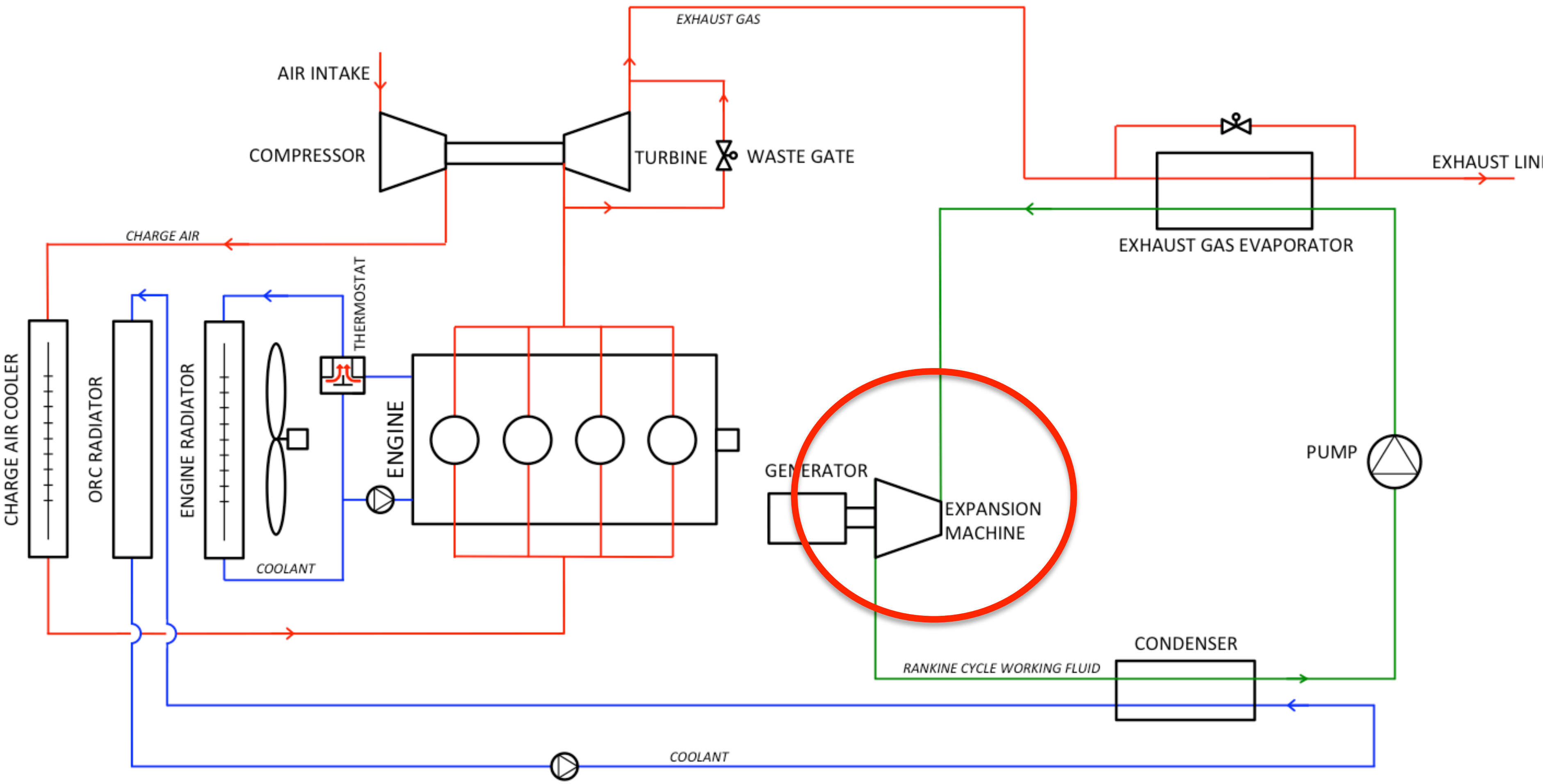
# DESIGN OF A SCROLL EXPANDER

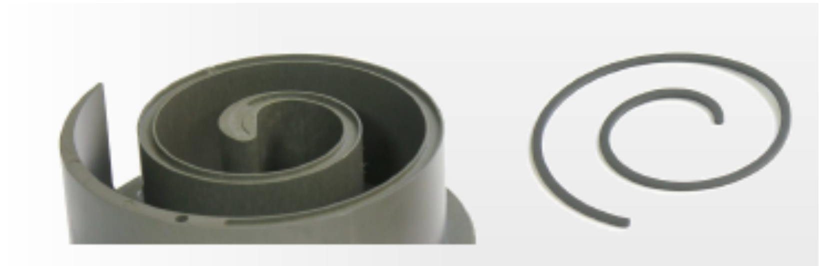
*Architecture of the Rankine cycle system*



# DESIGN OF A SCROLL EXPANDER

## *Choice of expansion technology*

- Previous works stressed the advantage of **scroll** machines (design simplicity, reliability, promising performance, etc.) and **water** or ethanol (or a mixture) as working fluid.



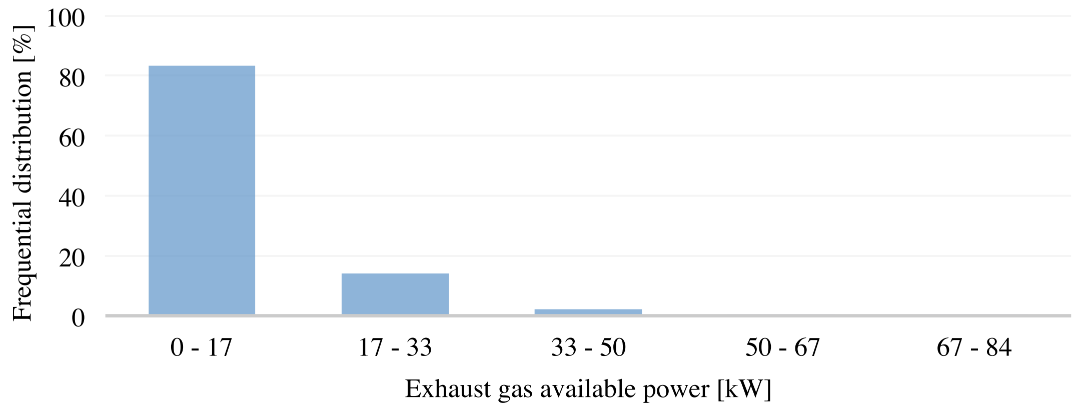
- However, no commercial **high temperature** scroll expander designed for such an application is available on the market.
- **Lubricating oil** may be a major issue in ORC systems, especially in steam Rankine cycle (high operating temperatures, oil separation require bulky apparatus not compatible with mobile applications).

→ An **high-temp., oil-free scroll expander** has been designed and **prototyped**.

# DESIGN OF A SCROLL EXPANDER

*Which nominal point?*

- First step of the design is the sizing.
- The World Harmonized Light Vehicles Test Cycle (WLTC) was applied to a 120 kW gasoline engine.
- Frequential distribution of power available in exhaust gases indicates that most of the time, the engine power in located in the first class (0-17).



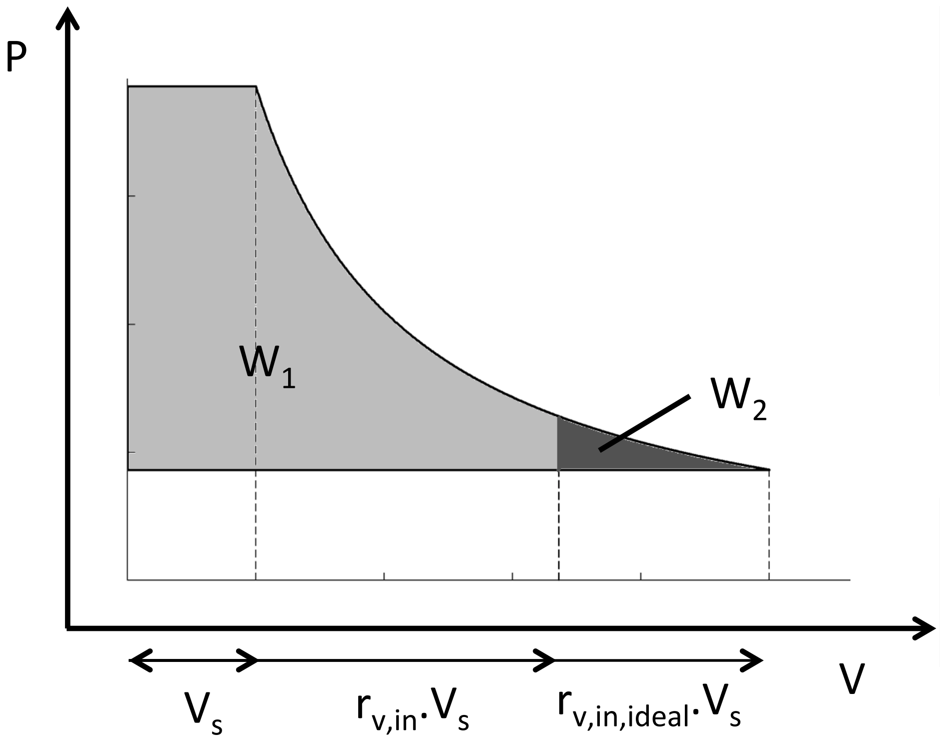

- However, operating conditions are highly transient.

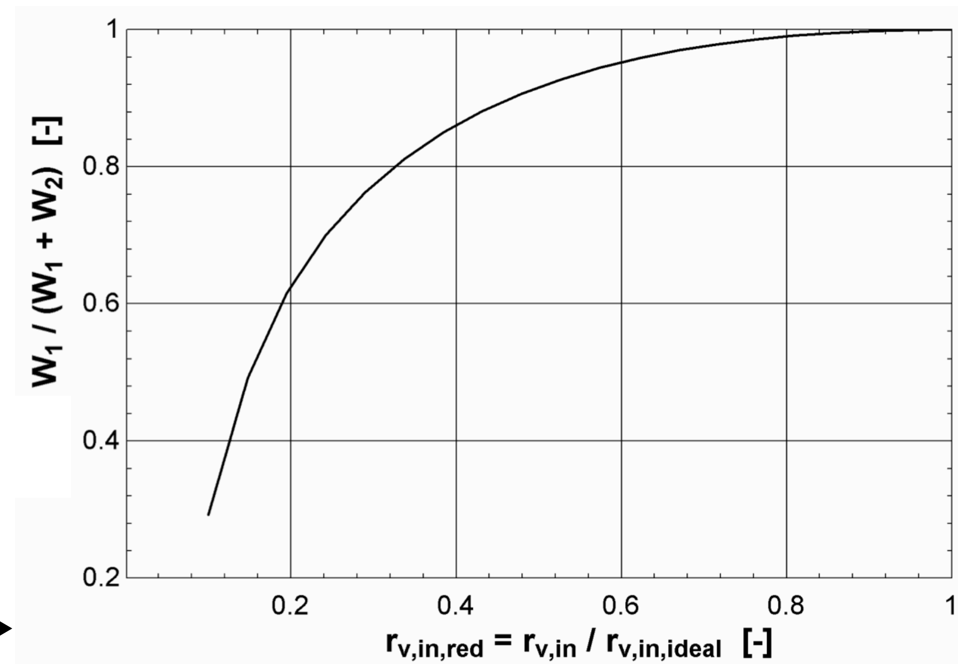
→ No nominal point can be easily defined and an optimization of the scroll characteristics (mainly, the displacement) has to be conducted.

# DESIGN OF A SCROLL EXPANDER

*Characteristics of the expander*

- **Volume Ratio**



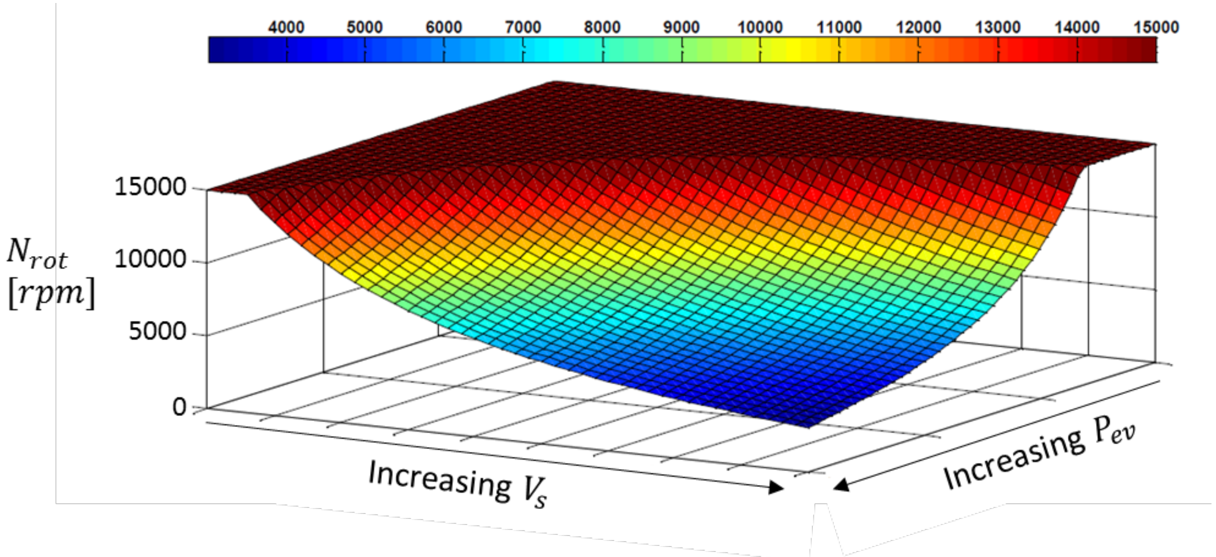




A built-in volume ratio lower than the optimal volume ratio has been selected for compactness. That should also allow for a reduction of internal leakages.

# DESIGN OF A SCROLL EXPANDER

## *Characteristics of the expander*

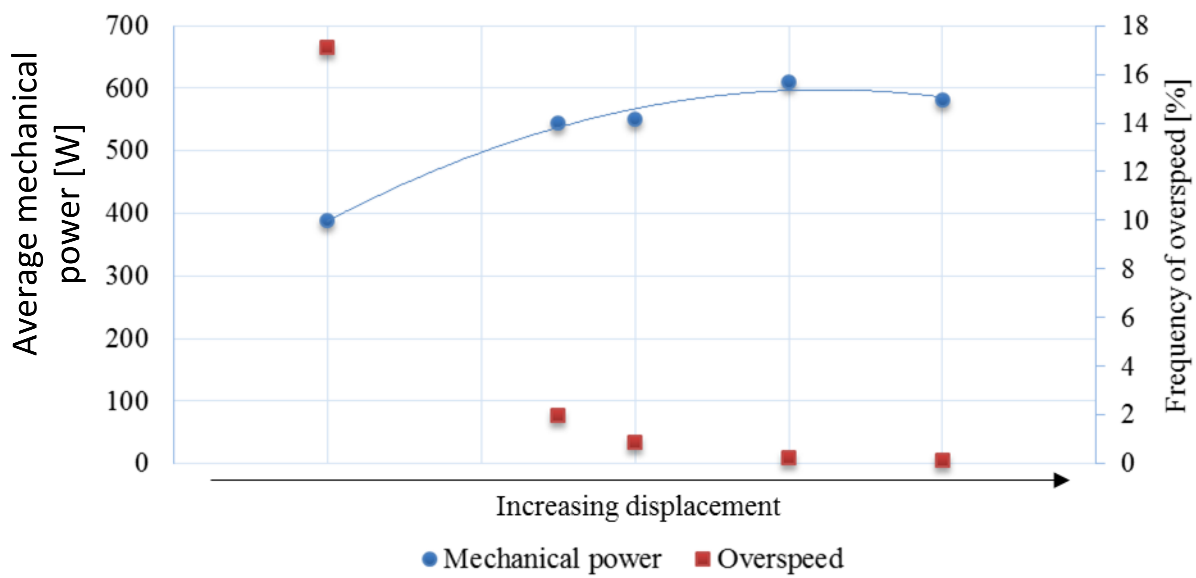
- **Displacement** is optimized based on quasi-static simulation of the Rankine Cycle system (including a grey-box expander model) over the driving cycle.
- The rotational speed is a function of the displacement and evaporating pressure
  - Low displacements or low pressures will yield high speed and the latter is constrained
  - Large displacements or high pressures will yield low speed and a larger impact of internal leakages



# DESIGN OF A SCROLL EXPANDER

*Characteristics of the expander*

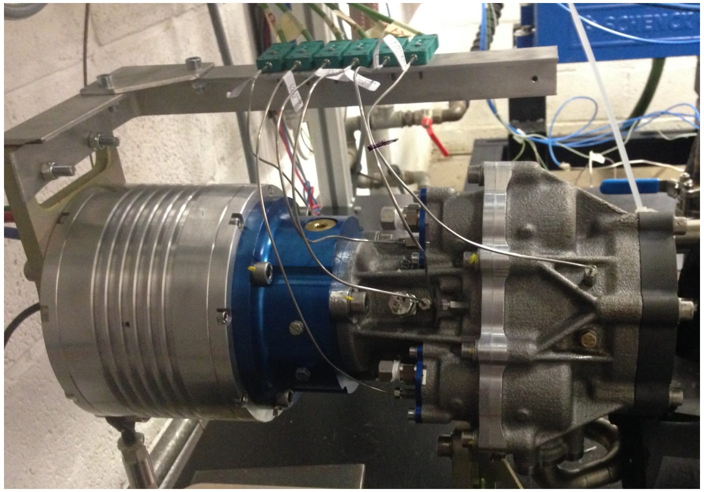
There exists an optimal displacement maximizing the average power produced by the Rankine cycle system over the driving cycle.

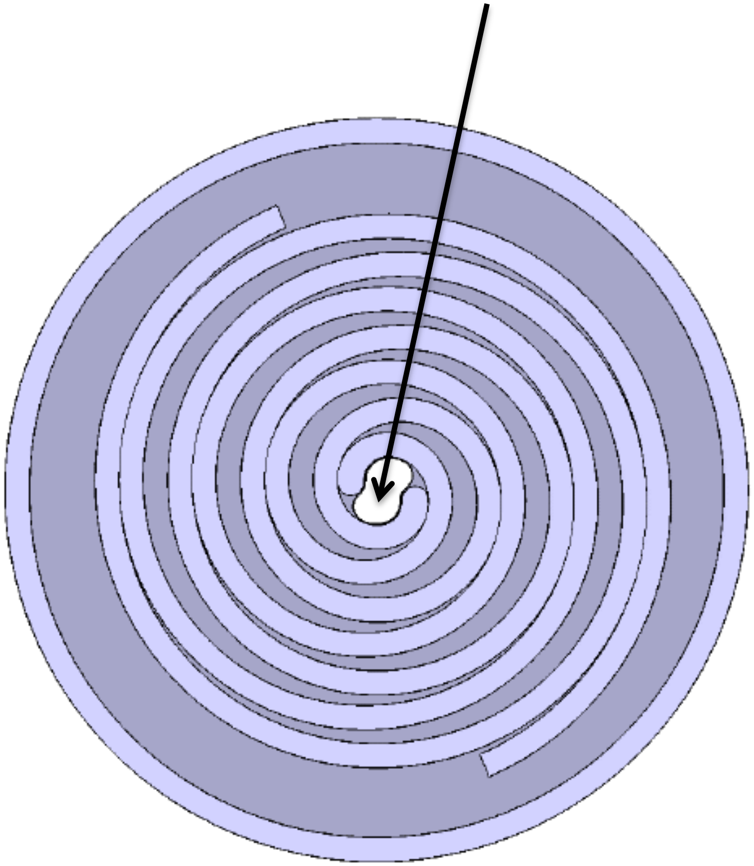


# DESIGN OF A SCROLL EXPANDER

## *Defining the geometry*

- A detailed scroll simulation model is used to define the exact geometry of the expander.
- Suction port cross-sectional area has been maximized by enlarging the clearance volume (which is not a drawback in expander mode)
- Oil-free concept was selected: involute in coated aluminum and tip seals in self-lubricating material.





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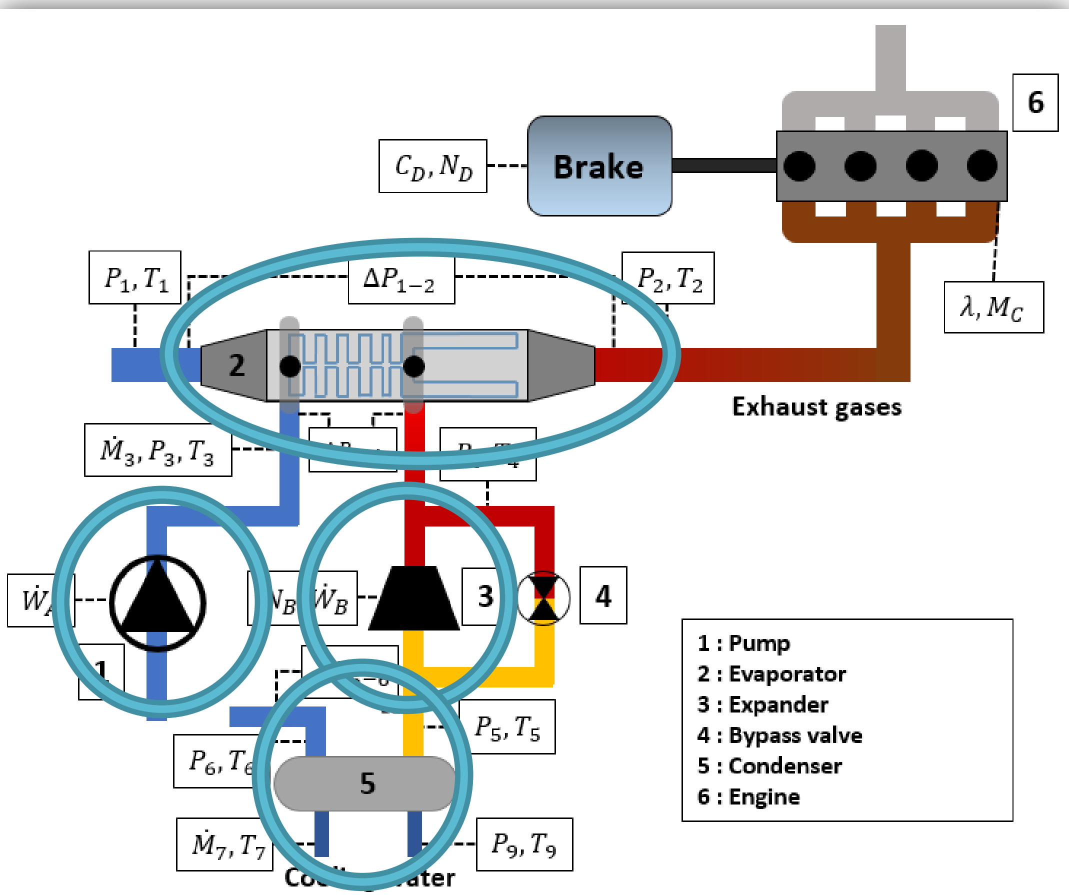
# TESTS ON PROTOTYPES

*Description of the test rig*



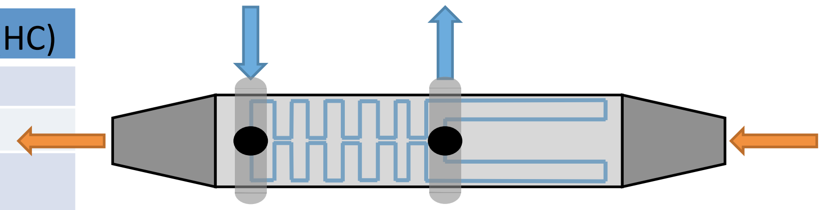

- Open-loop steam Rankine cycle
- Connected to a gasoline engine
- Produced electricity dissipated in electric resistances

# TESTS ON PROTOTYPES

*Evaporator*

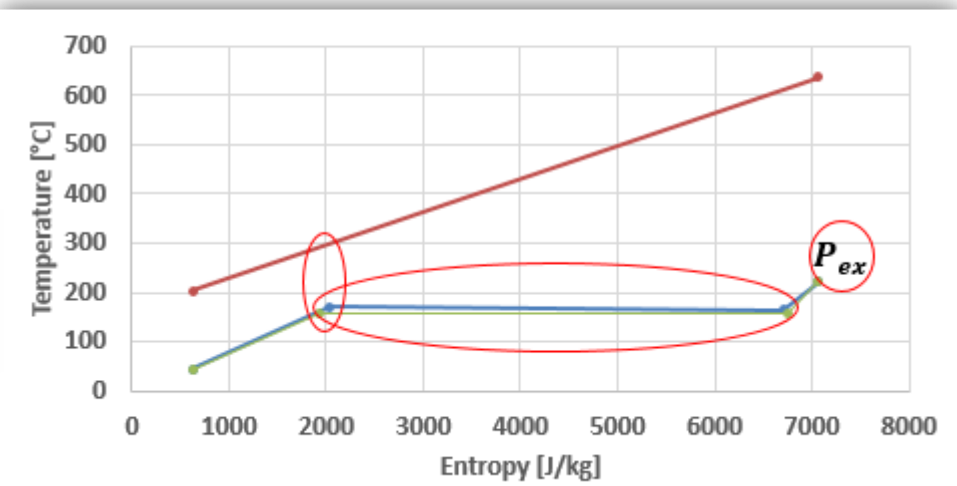
- Two heat exchangers configurations tested: counter-current and hybrid current

| Type of evaporator | Counter Current (CC) | Hybrid Current (HC) |
|---|---|---|
| Mass [kg] | x | 1.77.x |
| Volume [dm³] | y | 0.83.y |
| Water exchange area [m²] | z | 0.36.z |



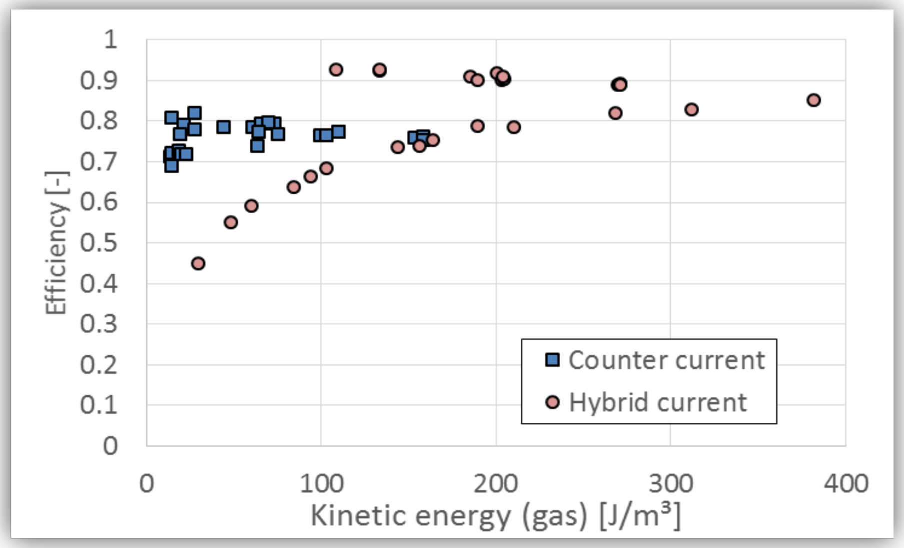
- Performance expressed in terms of efficiency and pressure drops.
- Evaporator efficiency: ratio between the actual and maximal heat transfer rates

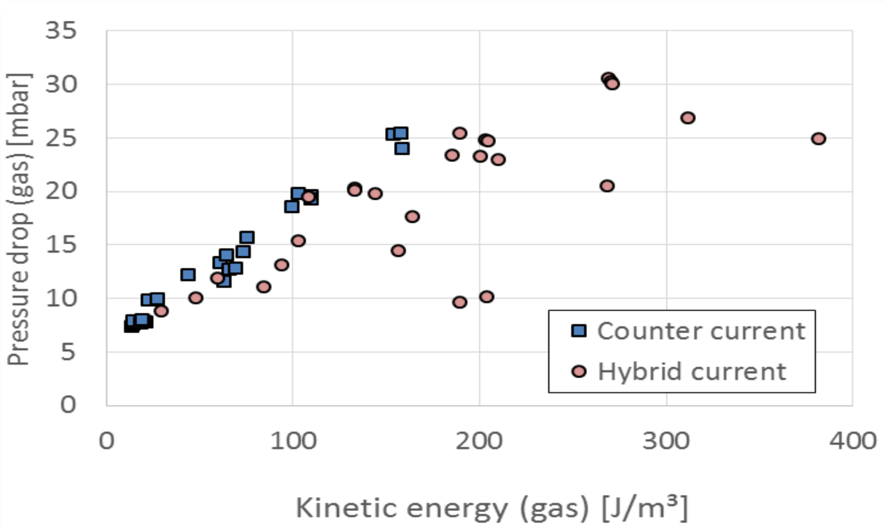
$$\eta_{ev} = \frac{\dot{M}_{eg} c_{p,eg} \left(T_{eg,su} - T_{eg,ex}\right)}{\dot{M}_{eg} c_{p,eg} \left(T_{eg,su} - T_{w,satEx}\right) + \dot{M}_w \left(h_{w,sat} - h_{w,su}\right)}$$

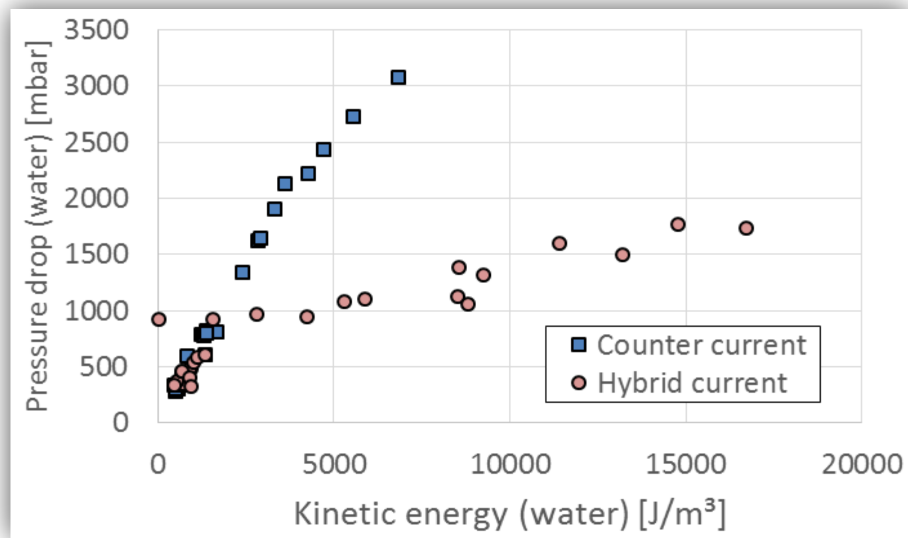


# TESTS ON PROTOTYPES

*Evaporator*



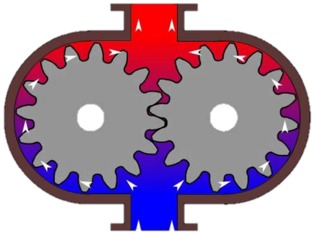




- Large efficiencies
- Low pressure drop on the gas side
- Higher pressure drop on the water side (especially the CC)

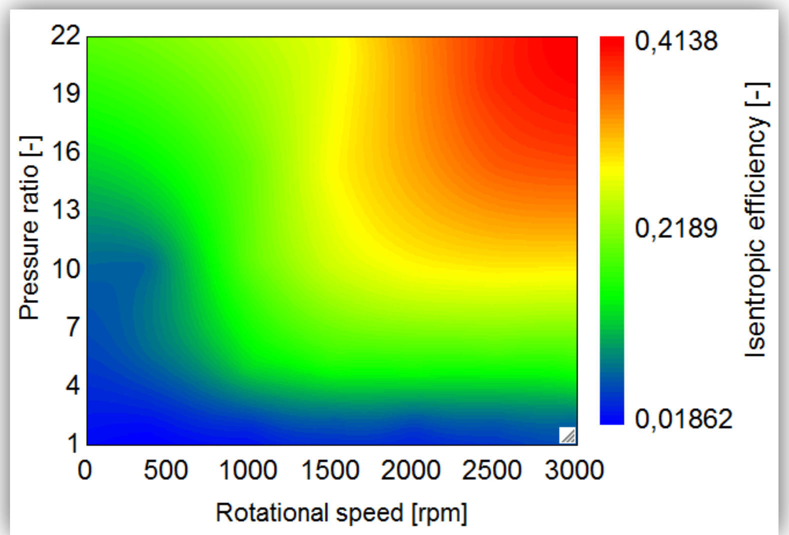
# TESTS ON PROTOTYPES

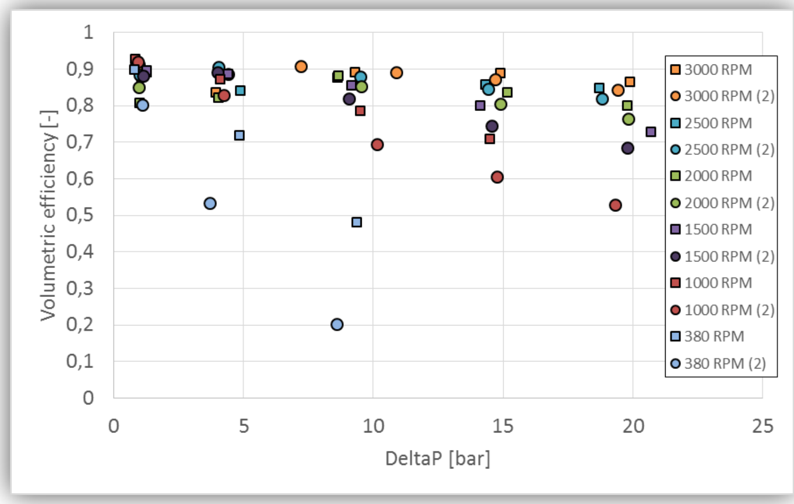
## *Pump*

- Gear pump
- Performance expressed in terms of isentropic and volumetric efficiencies
- Maximum isentropic efficiency = 45%
- Maximum volumetric efficiency = 90%



| Parameter | Value |
|---|---|
| Swept volume | 0.5 $cm^3$ |
| Max. pressure | 20 bar |
| Max. mass flow (3000 RPM) | 20 g/s |
| Max. power consumption | 105 W |

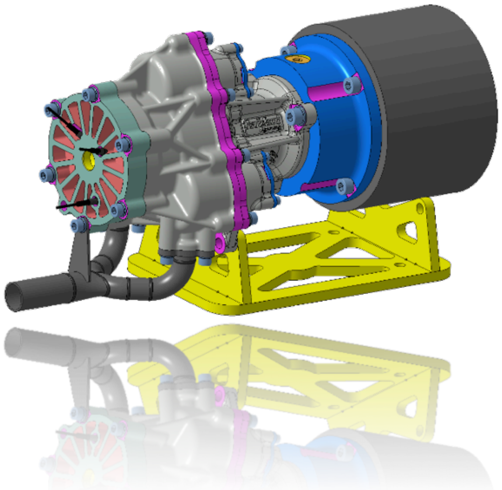


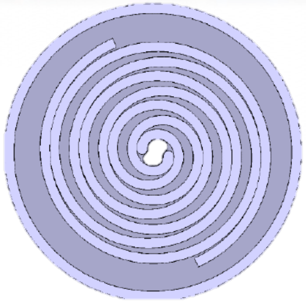



# TESTS ON PROTOTYPES

## *Expander*

- Taylor made expander presented previously.
- Two generations of expanders have been built: V1 and V2 (20% reduced scroll lateral clearance).



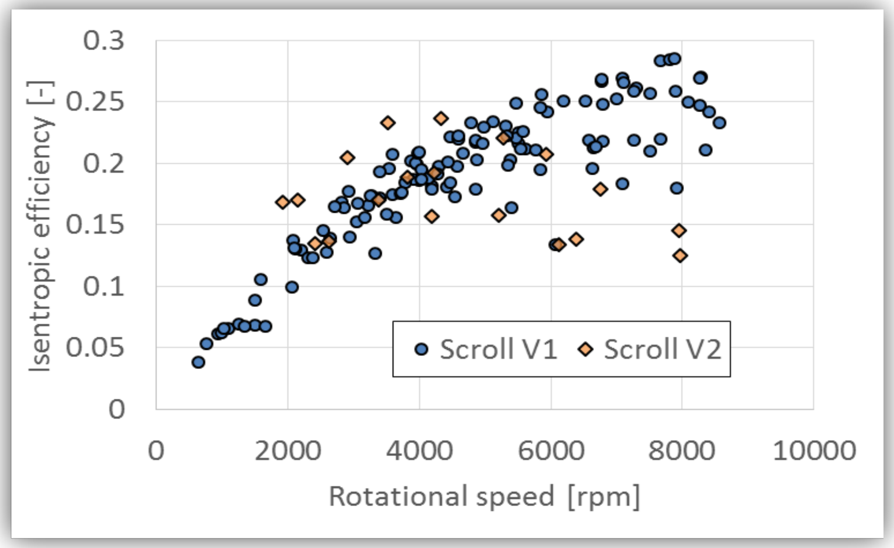


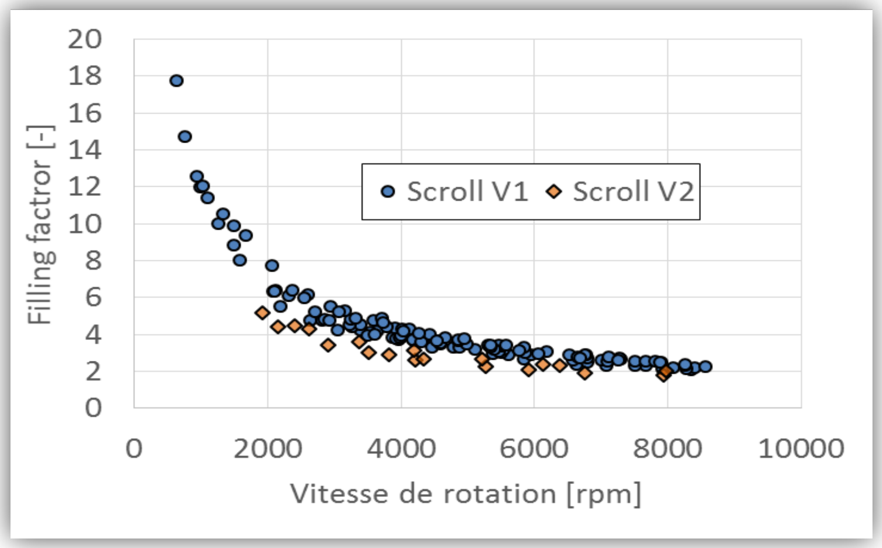
| Parameter | Value |
|---|---|
| Swept volume | 8 $cm^3$ |
| Max. rotational speed | 15 000 RPM |
| Max. temperature | 250°C |
| Pressure | Up to 20 bars |
| Volume ratio | Confidential |

# TESTS ON PROTOTYPES

## *Expander*

- Performance expressed in terms of isentropic efficiency and filling factor.
- Max isentropic efficiency of 28% is achieved.

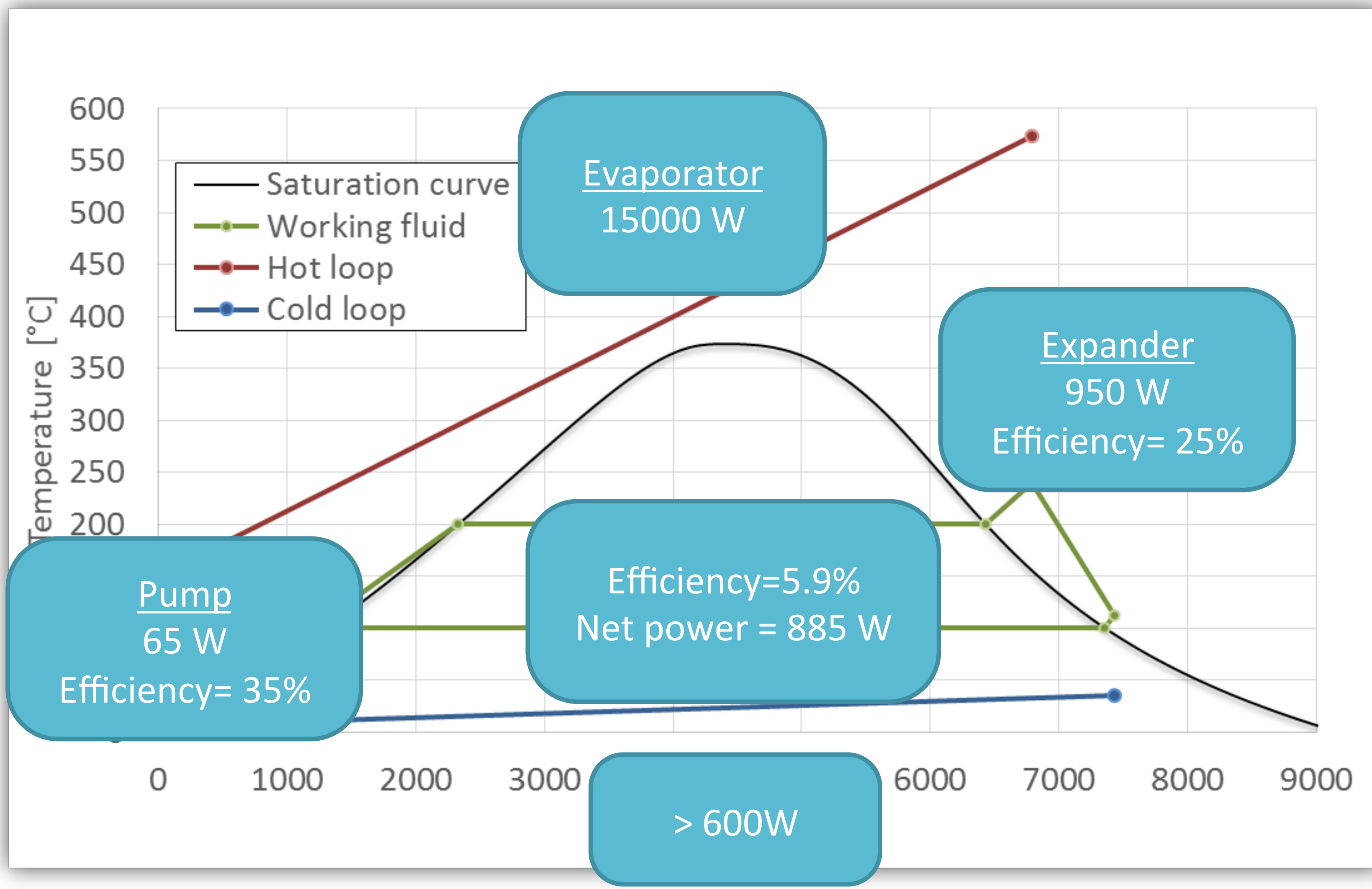



- Very low efficiency is explained by important internal leakages.
- For V2: optimal rotational speed of 4000 rpm (antagonistic effects of speed on mechanical losses and leakages)

# TESTS ON PROTOTYPES

*Overall performance*



# Conclusions and perspectives

- ✧ A **model-based comparison** of different waste heat recovery techniques has been conducted, highlighting the **Rankine** cycle system.
- ✧ A **high temp. oil-free scroll expander** has been designed, prototyped and tested. There is a large potential of performance improvement.
- ✧ A pump and 2 evaporators have also been tested showing good performance.
- ✧ A reduction of **BSFC of 5%** on a NEDC is achievable.

- ✧ Perspectives:
  - Tests with ethanol or with a mixture of water/ethanol will be conducted.
  - Test with oil will be conducted.
  - Other components will be tested.
  - Waste heat recovery on engine cooling loop will be investigated.

Thank you for your attention!

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