Improving Train Energy Efficiency by Organic Rankine Cycle (ORC) for Recovering Waste Heat from Exhaust Gas

Paper ID: 193

ASME International Gas Turbine Institute | ORC15

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Agenda

- 1. Objectives and context
- 2. Sizing the ORC
  - Heat recovery potential
  - Screening the working fluid
  - Expected performances
- 3. Prototype and testing setup
  - ORC architecture
  - Implementation at engine test bench
- 4. Experimental results
  - Steady-state evaluation
  - Boiler hunting limitation
- 5. Conclusions

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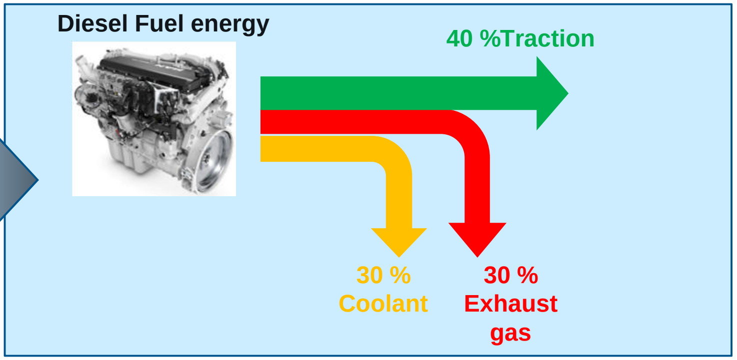
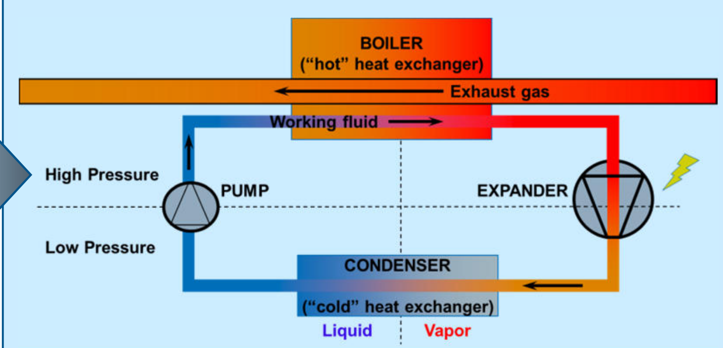
1. Objectives and context

Train application

- **700 Regional trains in Europe**
  - **30% full electric, 23% Diesel and 47% dual-mode**
  - **Diesel engines linked to high-power generators for electric traction (>300kW and >50L/100km)**
- **Energy balance**
  - **60% of the fuel energy content is lost : 30% in exhaust gas + 30% in coolant**
  - **Exergy analysis shows that more energy is recoverable from exhaust gas than from engine coolant**
- **ORC is a proven solution for waste heat recovery:**
  - **Exists in serial for stationnary engines (biogas gensets, marine) ➔ steady-state conditions**
  - **Challenging to apply it onboard a train ➔ transient conditions**
  - **Expander could be a turbogenerator to reinject the produced electricity in the electric train grid**





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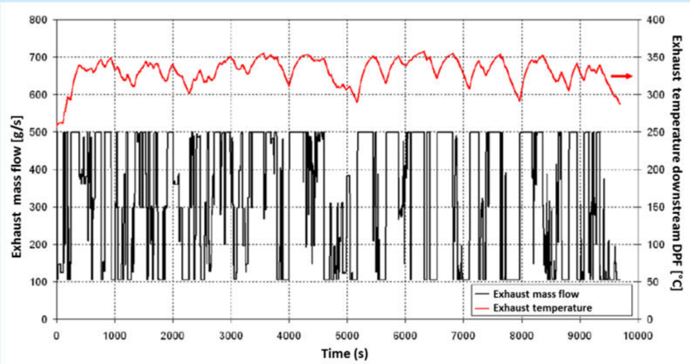
2. Sizing the ORC

Heat recovery potential

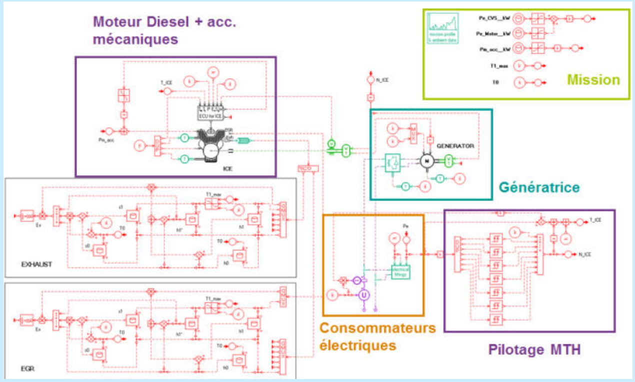
■ Exergy simulation on real profiles

$$\Delta Ex_{12} = (H_2 - H_1) - T_0.(S_2 - S_1)$$

INPUTS real mission profiles (exhaust mass flows and T, engine and generator powers)



SIMULATION 0D low-frequency model of train Diesel engine and generator (on AMESim platform)



RESULTS w/ assumptions (recovery on exhaust gas only with ORC boiler after DPF Diesel Particulate Filter)

	ORC Configuration	1.	2.	4.	3.	5.
	Cold sink T [°C]	50°C	50°C	25°C	50°C	50°C
	Max. fluid T [°C]	No limitation	No limitation	200°C	200°C	150°C
	Boiler position	Just after DPF	1m downstream DPF	Just after DPF	Just after DPF	Just after DPF
High speed profile →	Exergy on profile A [% mech. energy]	48kW (14%)	24kW (7%)	42kW (13%)	39kW (12%)	36kW (12%)
Stop & Go profile →	Exergy on profile B [% mech. energy]	49kW (14%)	24kW (7%)	41kW (13%)	38kW (11%)	36kW (10%)

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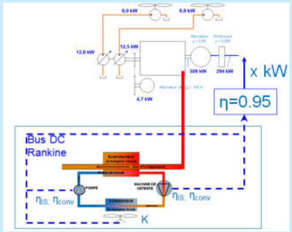
2. Sizing the ORC

Screening the working fluid

ORC simulations with parametric variations

SIMULATION

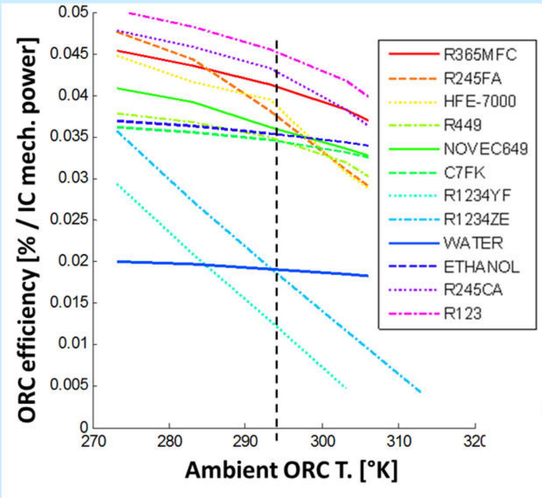
- ORC 0D steady-state model using Matlab platform
- RefProp database for fluid properties
- Assumptions on ORC components efficiencies
- ORC efficiency evaluation for engine max power point
- 100 different fluids tested
  - Water
  - Ammonia, SO2
  - Hydrocarbons, Alcohols
  - HFC: Hydrofluorocarbons…

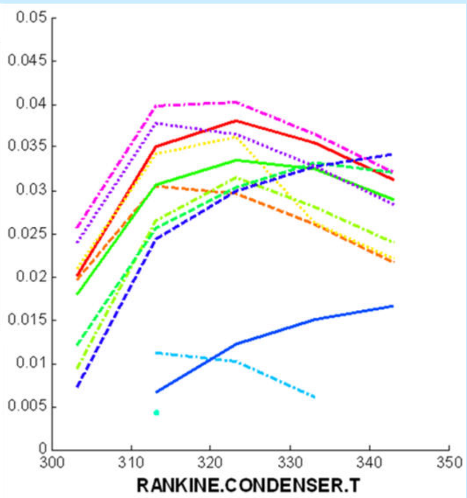


CRITERIA FOR FLUID SELECTION

- Thermodynamic performance: ↓ pump energy, ↑ exergy transfer ,↑ expansion energy recovery , ↓ energy of condensation
- Environment: not flammable and low toxicity, no ODP (Ozone Depleting Potential), low GWP (Global Warming Potential)
- Durability : chemical stability, material compatibility
- Cost

RESULTS





Fluid characteristic	R245fa	Fluid B
Formula	C3H3F5	Confidential
Max. continuous T	154°C	<300°C
Critical P/T	154°C 36,5bar	<200°C <20bar
Inflammability NFPA / HMIS	1 / 1 Non flammable	0 / 0 Non flammable
Toxicity NFPA / HMIS	2 / 2	Low
ODP GWP	0 950-1030	0 <50
Supplier Cost	Honeywell Medium	Confidential High

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2. Sizing the ORC

Expected performances

- **Predicted performances at max. power engine operating point**

Fluid	R245fa	Fluid B
Heat power received by the fluid in the boiler	134 kW	122 kW
Heat power lost by the fluid in the condenser	117 kW	107 kW
Electrical power generated by the turbine	16 kW	14 kW
Electrical pump power consumption	1,8 kW	1,6 kW
Cooling power consumption	5,8 kW	3,6 kW
ORC efficiency (compared to heat on fluid)	6,3 %	7,2 %
Fluid mass flow	2150 kg/h	3600 kg/h
P / T in HP branch	25 bar / 167 °C	15 bar / 200 °C
P / T in LP branch	3,6 bar / 41°C	1,5 bar / 50 °C

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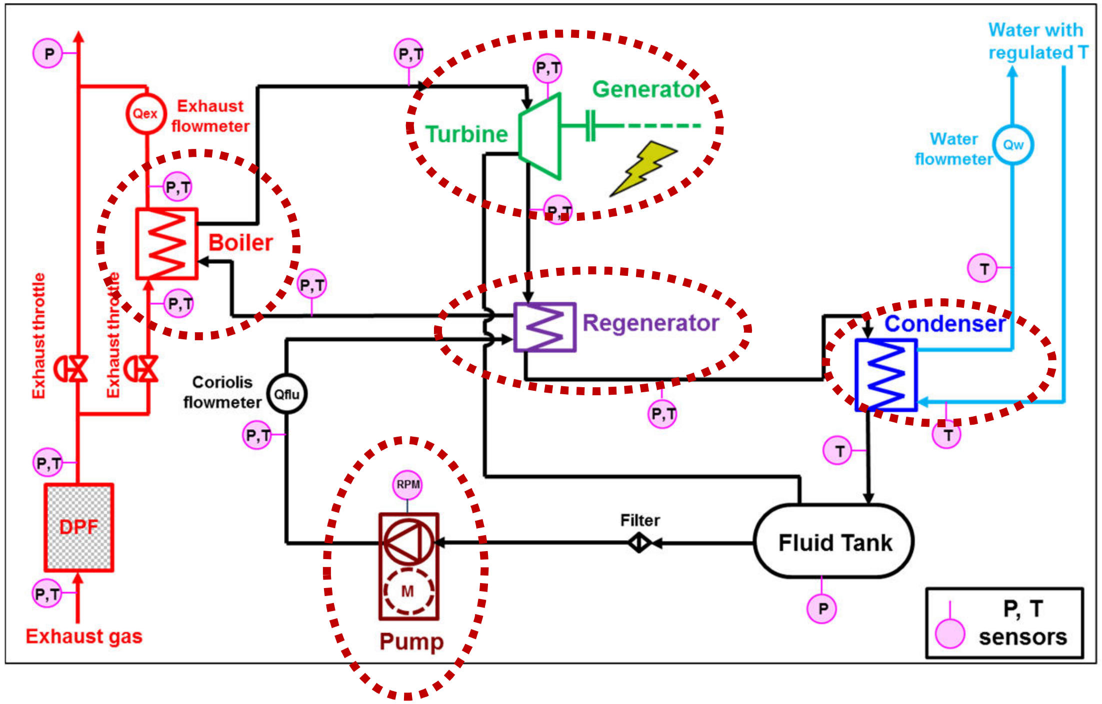
3. Prototype and testing setup

ORC architecture

- **Definition of ORC prototype layout**



- **Selection of ORC components with criteria of cost, availability, weight and compactness**
  - Industrial volumetric self-lubricated pump driven by an electric motor
  - Cross flow stainless steel boiler with mixing tubes (for fluid >3m²) and plates (for exhaust gas >50m²)
  - Axial turbine linked to a generator on same axle
  - Addition of a regenerator (pre-heating of the pressurized liquid with hot vapor after turbine expansion)
  - Off-the-shelf condenser
  - In-house control ORC ECU

- **Optimisation and design of turbine blades adapted to the 2 fluids (R245fa and fluid B)**
- **Prototype CAD: volume constraint (anticipation of ORC implementation on train)**
- **Prototype manufacturing and assembly**

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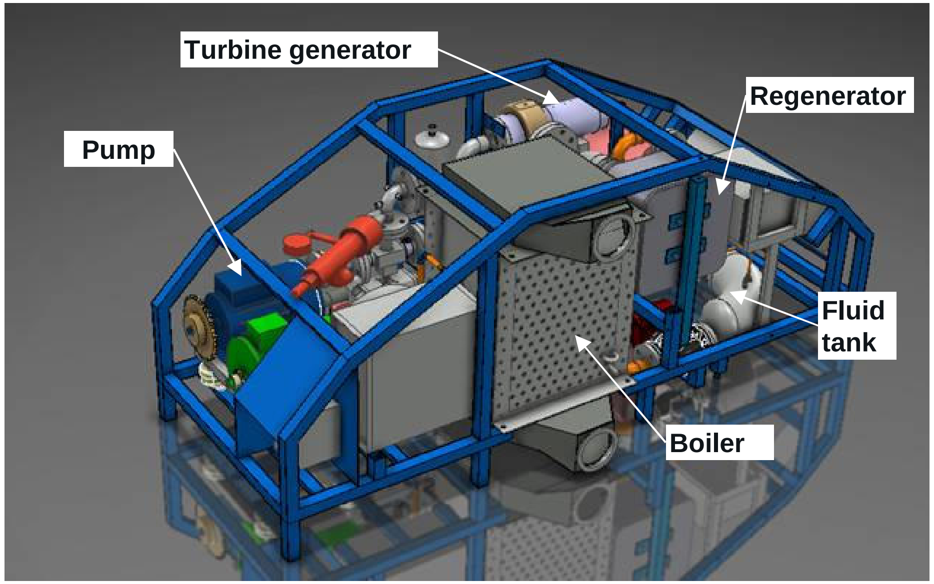
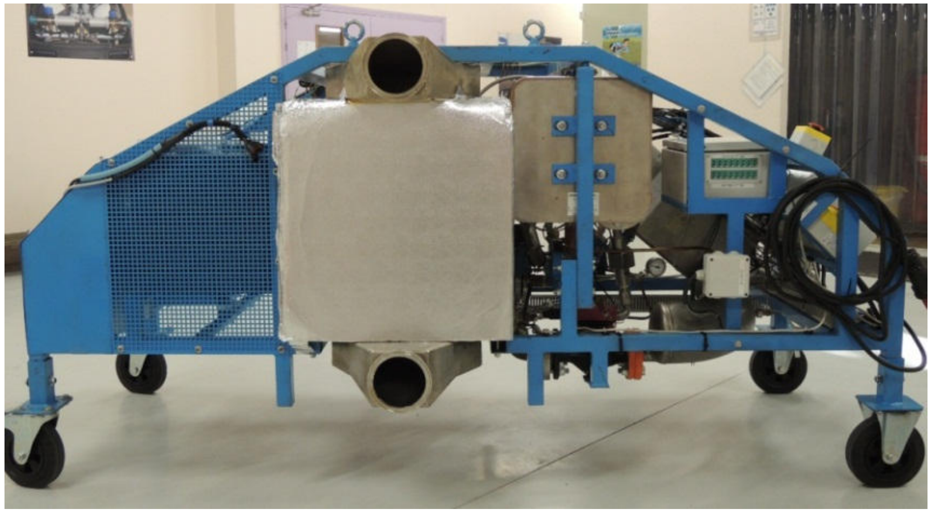
3. Prototype and testing setup

Prototype



CAD view of the prototype

Real view of the prototype



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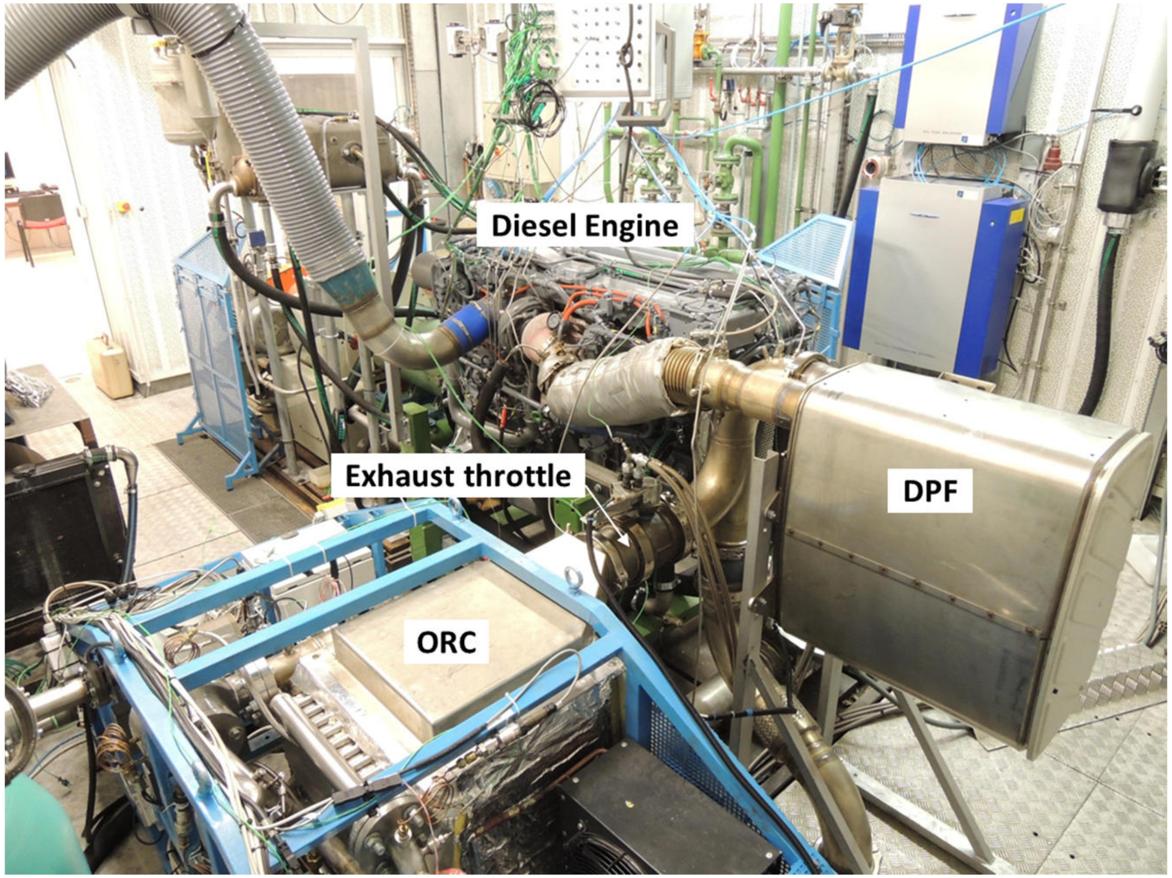
3. Prototype and testing setup

ORC implementation at engine bench



- **Same engine as in the train with its full exhaust line including DPF muffler**
- **Implementation of a smart inverter and transformer to measure ORC electric production**
- **Implementation of an ORC in-house control**
- **Real-time thermodynamical balance of the ORC during tests**
  - **ORC global efficiency**
  - **Every component efficiency**
  - **Mollier's diagram**
  - **P, T in the ORC loop**

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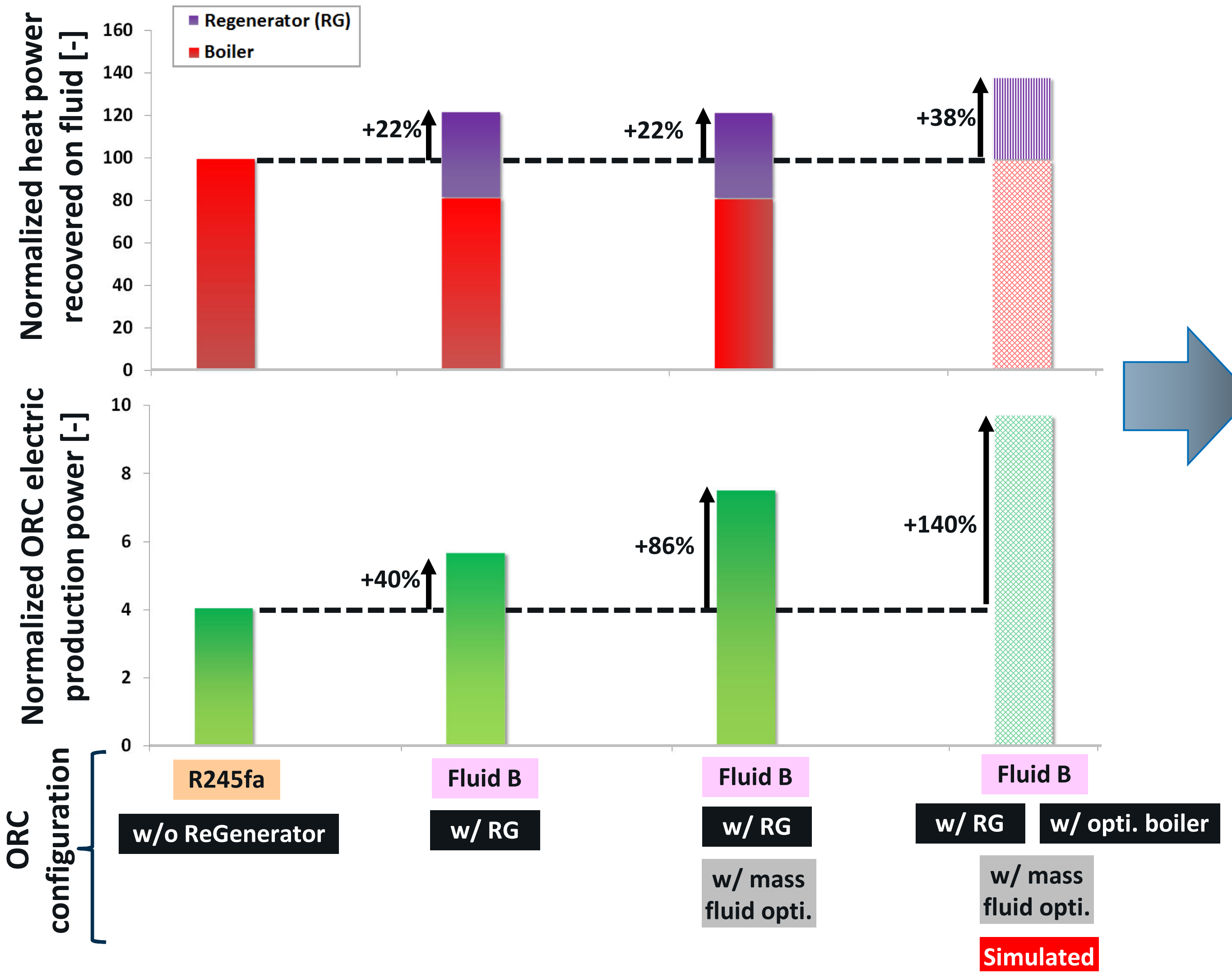
4. Experimental results

Results on the max. power engine point (>300kW)



10kW of ORC electric production in steady-state conditions at the engine test bench for an objective of 14kW evaluated by simulation

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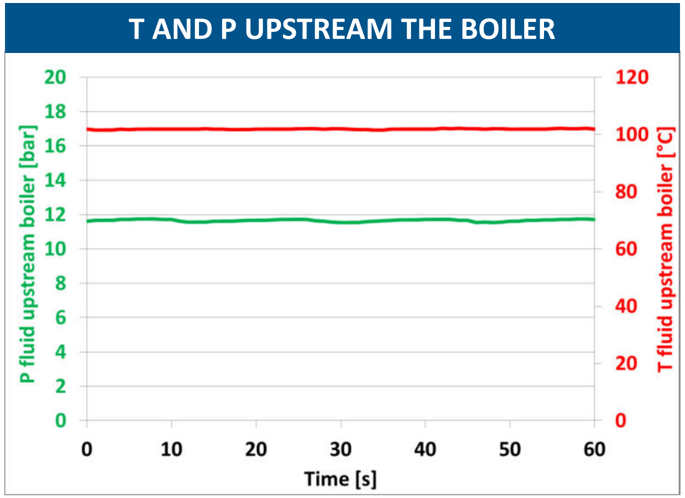
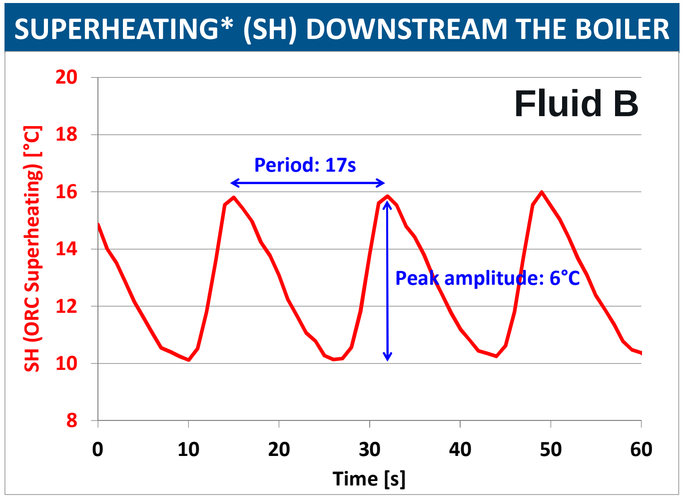
4. Experimental results

Boiler hunting limitation

- **Diphasic (gas/liquid) exchangers can oscillate in terms of T and P with stable input conditions: *« boiler hunting » phenomenon.***





- **The oscillation period and the amplitude depend on the working fluid**
  - **R245fa: SH period=40s, SH amplitude=8°C**
  - **Fluid B: SH period=17s, SH amplitude=6°C**
- **These oscillations must be suppressed to ensure a robust and consistent ORC control in transient conditions**

** SH is defined as the difference between the T downstream the boiler minus the T of vapor*

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5. Conclusions

From a blank sheet of paper … to an operational ORC prototype

- **Pre-industrial project for an ORC prototype ready to be implemented onboard a train. Different stages leading to an operational system:**
  - **Pre-sizing study for heat recovery potential by simulation**
  - **Screening of the different working fluids by simulation**
  - **Definition of the ORC architecture, selection of the components, manufacturing**
  - **Implementation on the engine test bench with real-time thermodynamical balance**
  - **Realistic tests with the same engine as in the train**
  - **Different stages of prototype evolution in order to increase ORC efficiency**
- **10kW of ORC electric production for the max. power engine point leading to an interesting fuel economy**

- **Outlooks**
  - **Evolution of the boiler to increase ORC global efficiency and limit the boiler hunting**
  - **Development of a robust dynamic ORC control for transient conditions**
  - **Integration onboard the train…**

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Thank you for your attention

Project partners:

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