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EXPERIMENTAL PERFORMANCE OF A MICRO-ORC ENERGY SYSTEM FOR LOW GRADE HEAT RECOVERY

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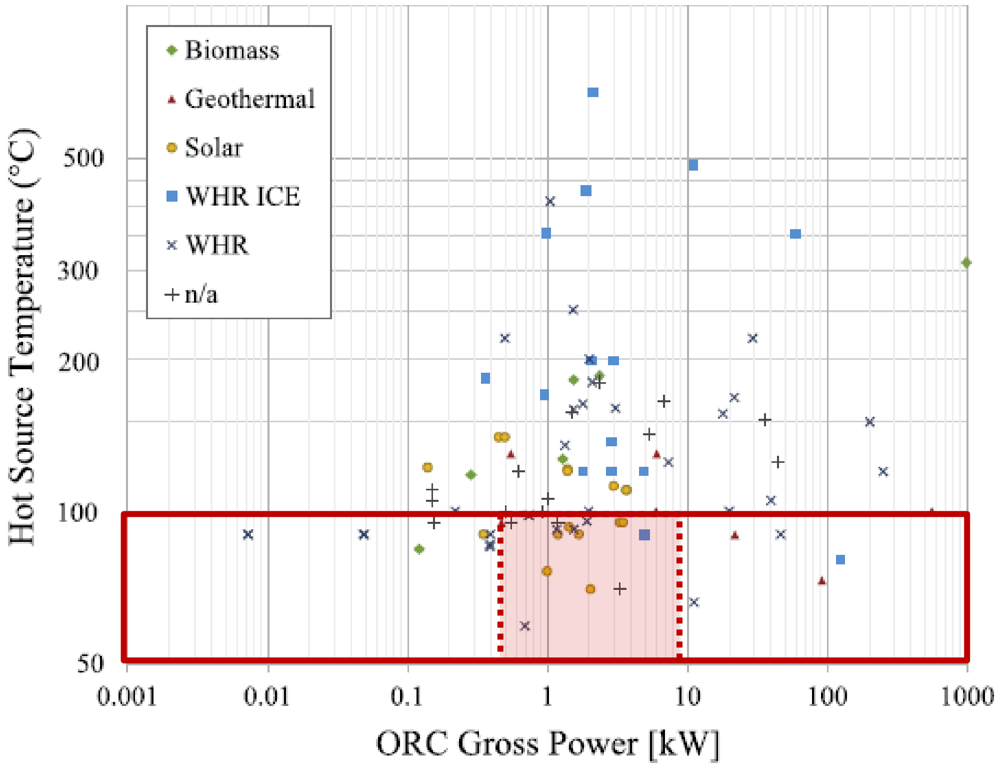
Outlines of the study

- ✓ Background and introduction
- ✓ μ-ORC test bench development: organic fluid circuit and external water supply lines
- ✓ Acquisition system project and implementation
- ✓ Test campaign setup: input parameters and data analysis methodology
- ✓ Steady state experimental results and discussion
- ✓ Conclusion and future steps

INTRODUCTION:
Background & Experimental activity on μ-ORC

Hot source temperature vs. ORC gross power map from open access ORC experiments database*



Low temperature and «micro-size» range application still not deeply investigated

* *A. Landelle, et al.* **ORC design and performance comparison based on experimental database**. Applied Energy 2017

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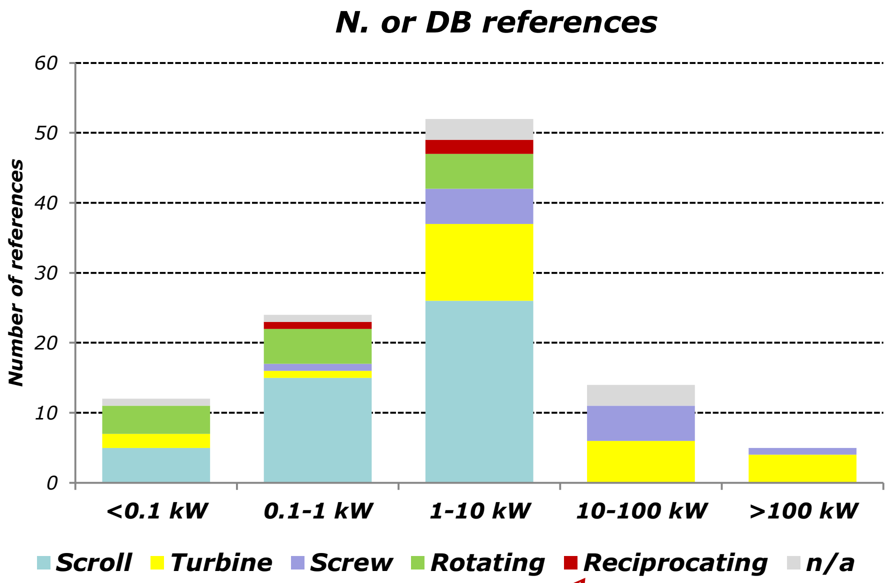

***Reciprocating expanders** less applied*

A. Landelle, et al. **ORC design and performance comparison based on experimental database**. Applied Energy 2017

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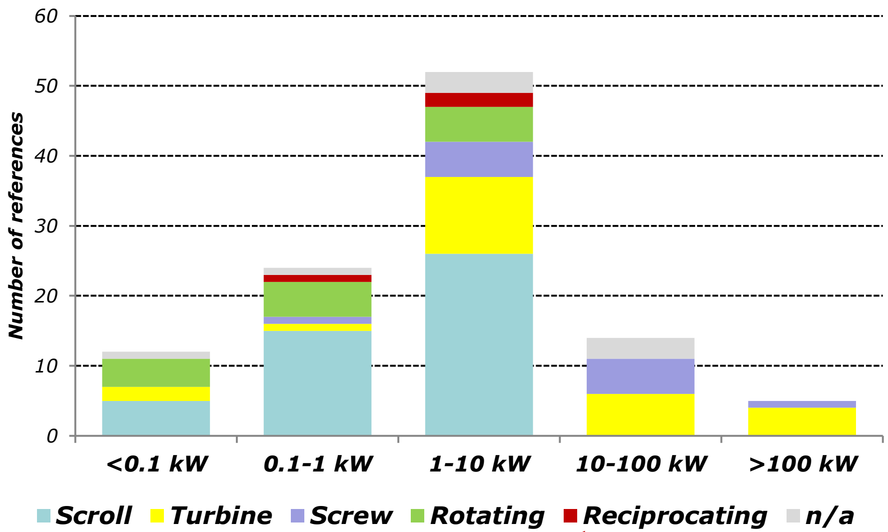


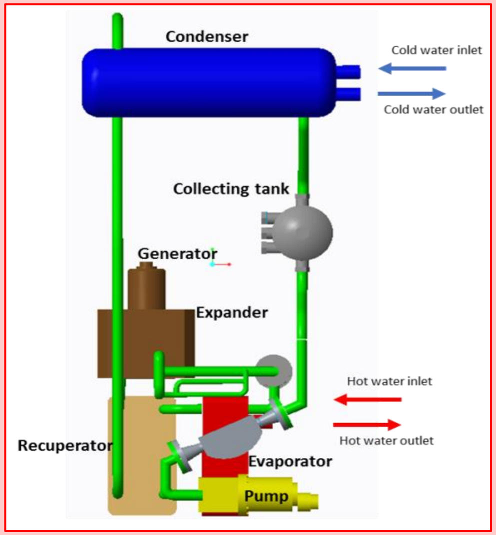
Reciprocating expanders *less applied*

Aim of our study:

Implementation of a new ***test bench*** to analyze prototypal μ-ORC energy system, characterizing its performance in ***steady-state*** conditions

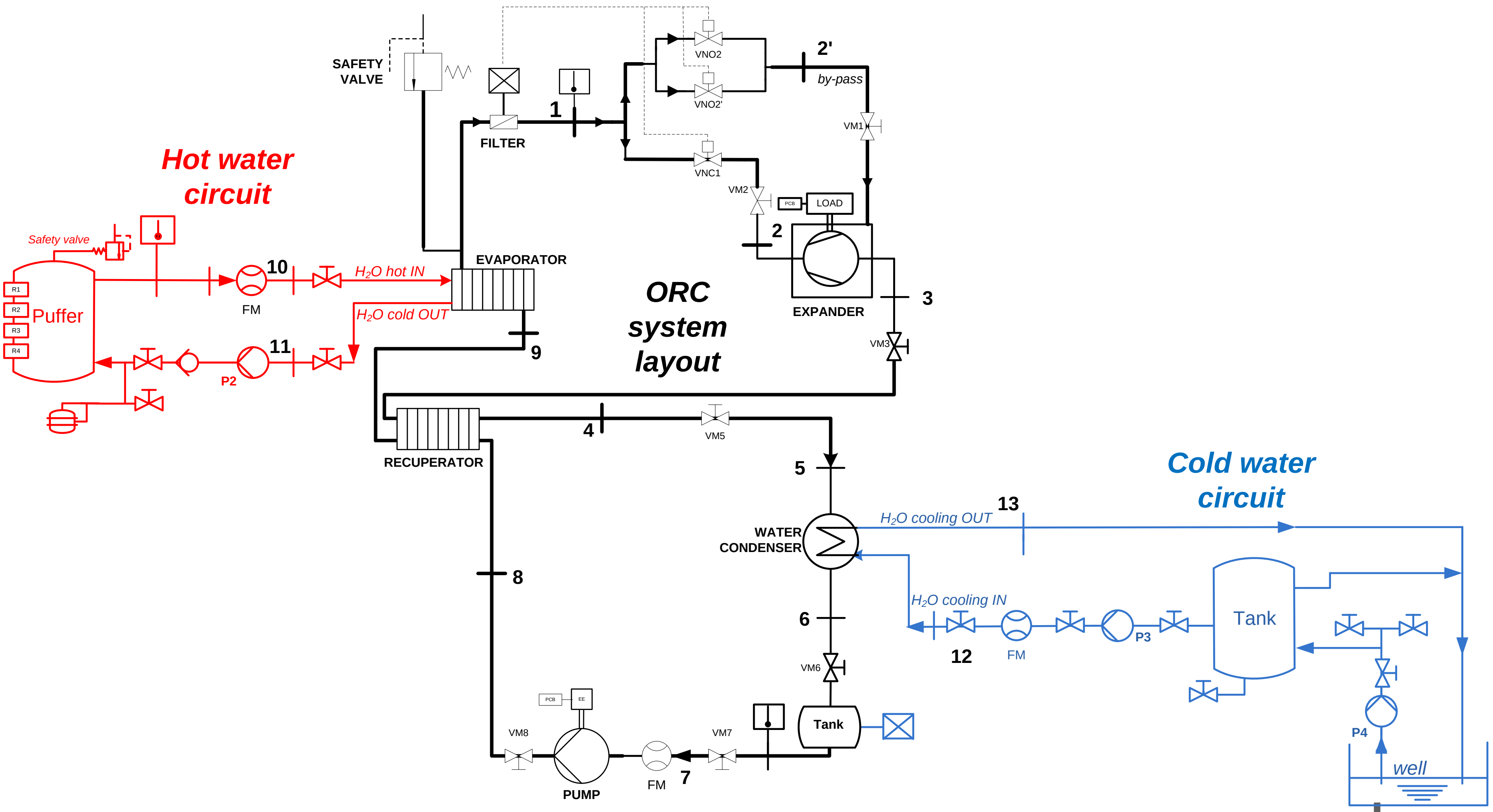
Main features

- Reciprocating piston expander (Star Engine™)
- Fitting for residential applications
- Working with low temperature heat source (50-90 °C),
- Regenerative cycle
- Working fluid HFC 134a



A. Landelle, et al. **ORC design and performance comparison based on**

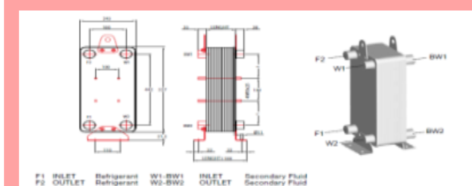
TEST BENCH - Layout

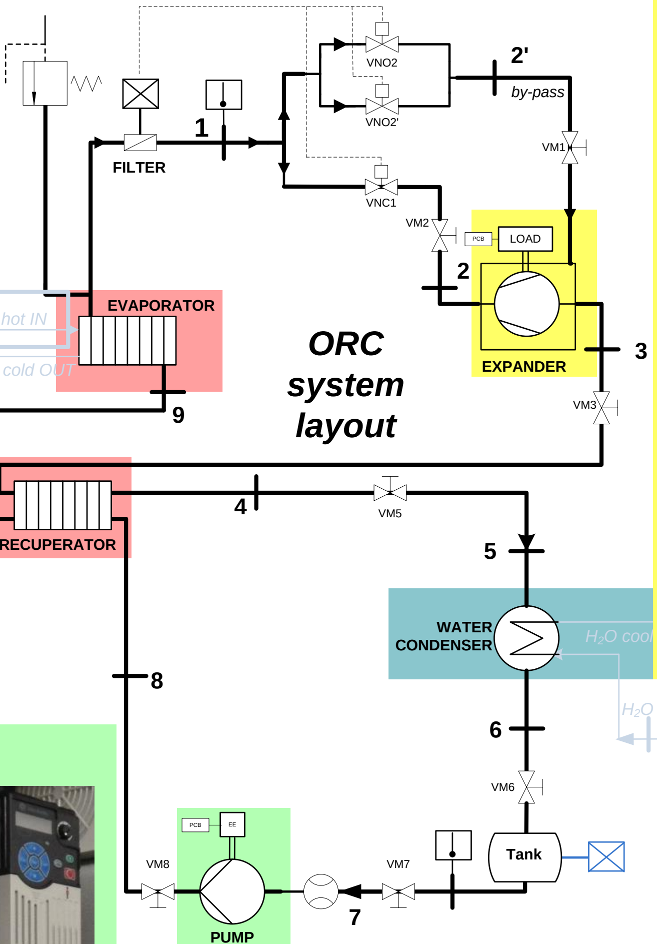


TEST BENCH – ORC System components

Evaporator and Recuperator

Commercial brazed plate heat exchangers (N=64; N=19)





Expander

Three radial pistons at 120°

Total displacement 230 cm³

Variable operating rotational speed: 0-1800rpm

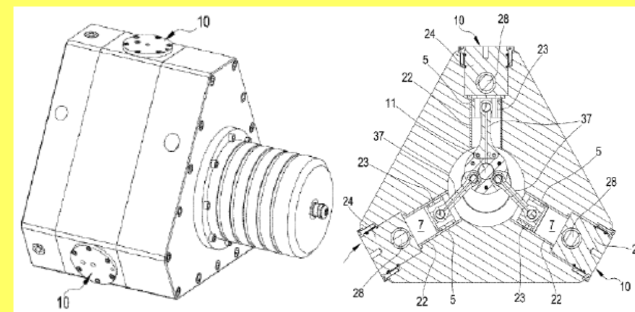
Synchronous 3-phase el. generator

Nameplate max output power 3 kW

Nameplate Voltage 380 V

Nameplate Efficiency 90%

Cooled with R134a



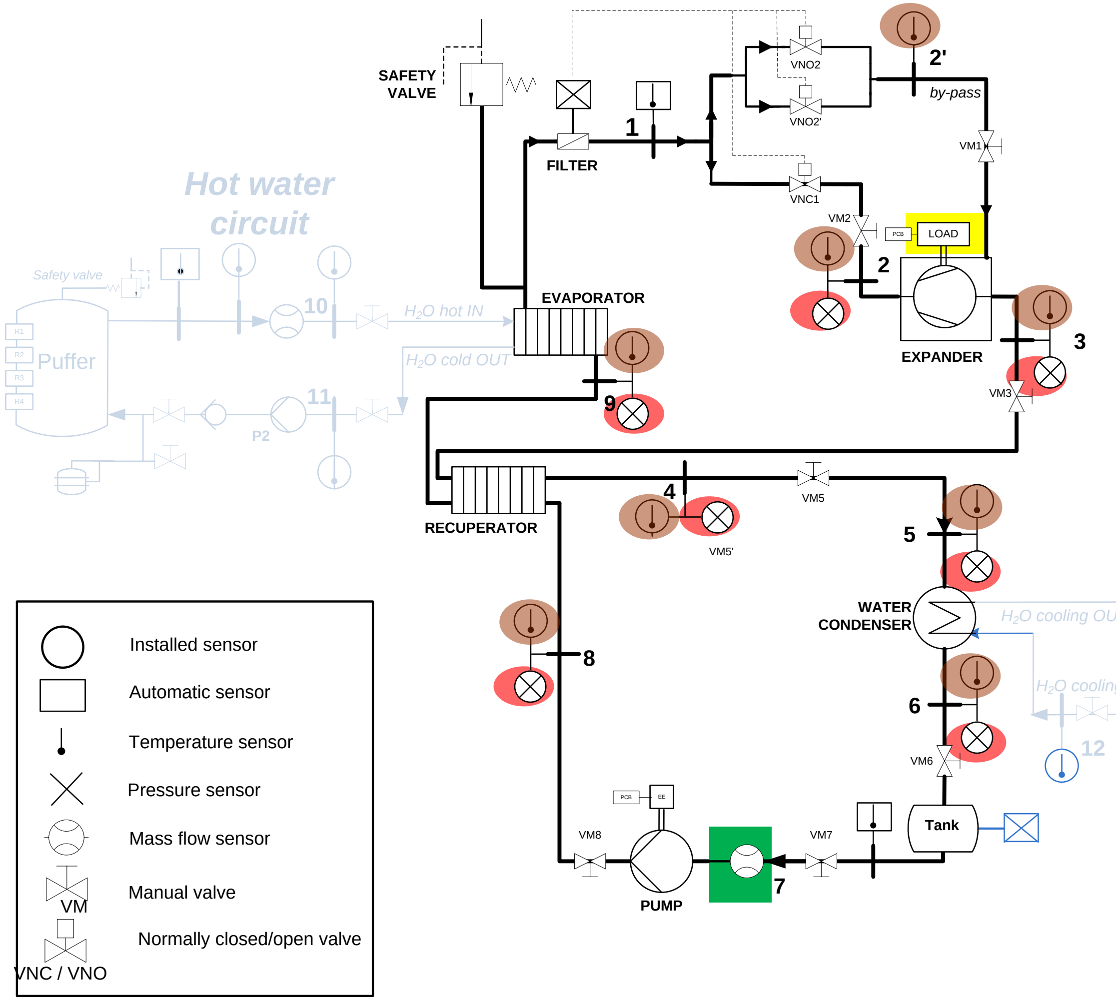
Prototypal gear PUMP + Variable Frequency Drive

(Allen Bradley PowerFlex)

Condenser

Commercial Shell and tube heat exchanger

TEST BENCH – ORC side instrumentation



Pressure transducers Honeywell FPA2000

T-type thermocouples

Coriolis Mass Flow Meter Endress+Hauser

Density acquisition

PCB: acquisition of three-phase electric power generation

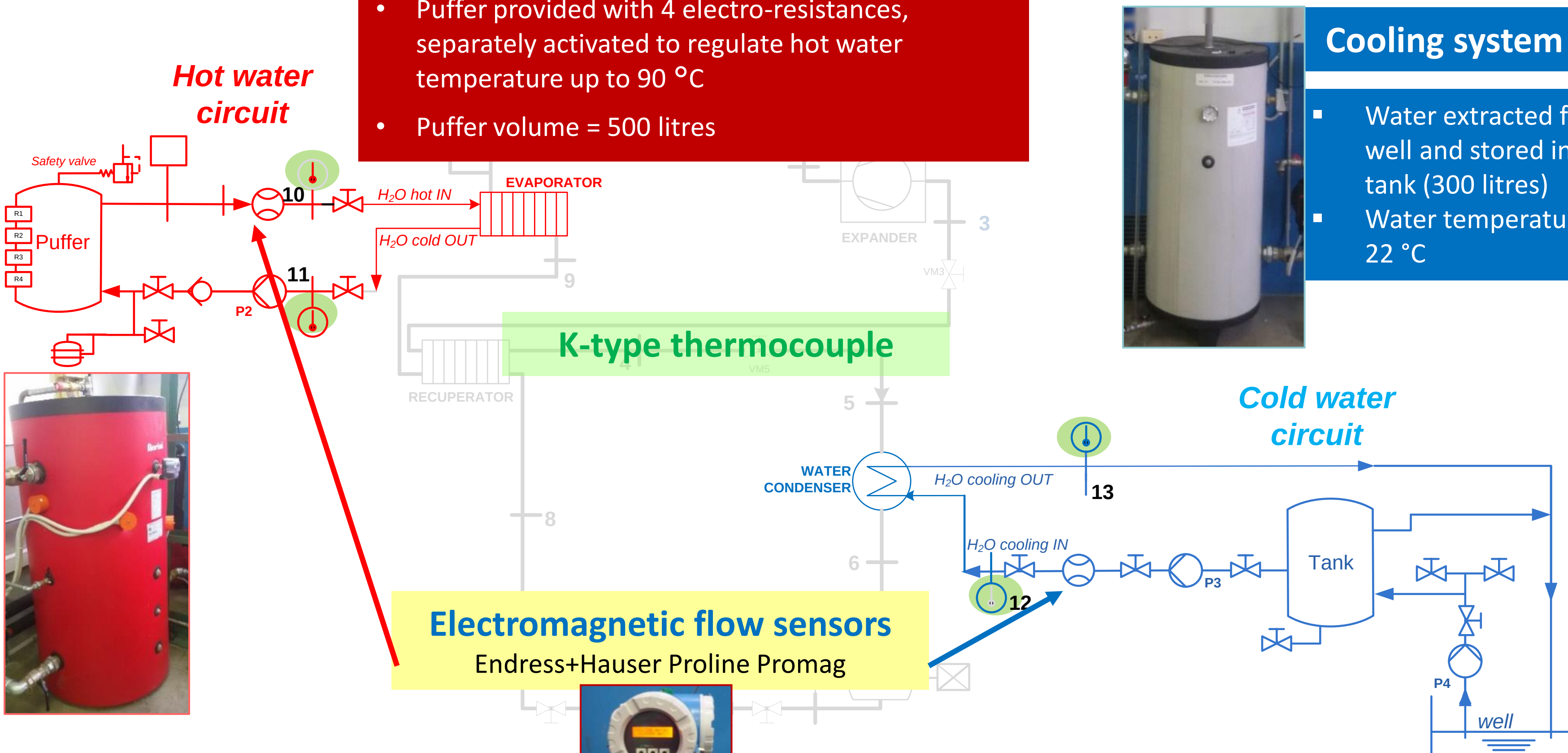
TEST BENCH – Water side

Heat source

- Water heated by a 32 kW electric puffer, circulated by centrifugal pump
- Puffer provided with 4 electro-resistances, separately activated to regulate hot water temperature up to 90 °C
- Puffer volume = 500 litres

Cooling system

- Water extracted from a well and stored in a cold tank (300 litres)
- Water temperature = 15-22 °C



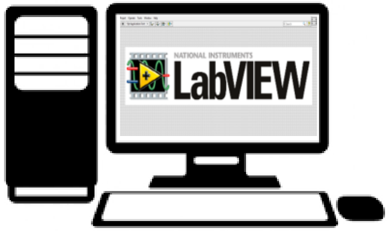
TEST BENCH – List of sensors

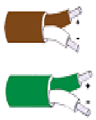
Physical quantity	Layout point	Sensor	Calibration range	Output signal	Accuracy	Input module
ORC Temperatures	2, 2’, 3, 4, 5, 6, 8, 9	T-type thermocouple	0-90 °C *	± 80 mV	0.5 K	NI9213-Thermocouple input
ORC Pressures	2, 8, 9	Pressure transducer	0-20 bar *	0-5 V	0.25 % FS *	NI9207- Voltage AI
	3, 4, 5, 6		0-10 bar *			
ORC mass flow rate	7	Coriolis mass flow meter	0.05-1 kg/s **	4-20 mA	0.3 % RV *	NI9207-Current AI
ORC density			10-1300 kg/m^3**	4-20 mA	0.1 kg/m^3 *	
Hot water temperatures	10, 11	K-type thermocouple	0-90 °C *	± 80 mV	0.5 K	NI9213-Thermocouple input
Cold water temperatures	12, 13			± 80 mV	0.5 K	
Hot water flow rate	10	Magnetic flow meter	0-6.4 l/s **	4-20 mA	0.5 % RV *	NI9207-Current AI
Cold water flow rate	12	Magnetic flow meter	0-9.8 l/s **	4-20 mA	0.5 % RV *	
Electric current and voltage	-	PCB mounted voltage transducer coupled with Rogowski coil current sensor	0-400 V ** 0-5 A **	0-4 V	0.1 % RV 0.2 % RV	

* Calibration performed in the laboratory
**Provided by sensor manufacturer

TEST BENCH – Acquisition system

Sensors → **National Instruments FPGA device** → **Workstation**





0-80 mV →

NI 9213 16 Ch. Thermocouple input
1 Sa/s

0-5 V →

4÷20 mA →

NI 9207 16 Ch. Analog input ± 20 mA / ± 10 V
1 Sa/s

0-5 V →

NI 9201 8 Ch. Analog input ± 10 V
100 kSa/s

T [°C]   p [bar]

↓

CoolProp
R134a

CALC COOL PROP

h *[kJ/kg]* ***s*** *[kJ/kg·K]*

m_{ORC} *[kg/s];* P_{el} *[kW]*

↓

Real-time performance evaluation

TEST CAMPAIGN – Data processing

Steady state detection (SSD) methodology

1. Proposed by Woodland et al. (2012)

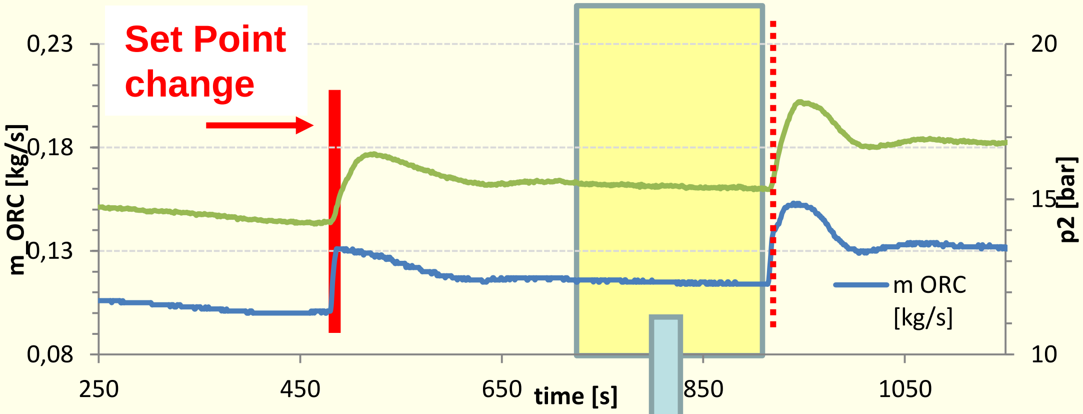
a) Comparison between averaged values of two set of data, taken ten minutes in-between

b) The percentage variation between the two consecutive averaged values is computed and compared to specific thresholds

Measured quantity	Threshold
Temperature	Δ < 0.5 K
Pressure	Δ < 2 %
Mass flow rate	Δ < 2 %
Rotating speed	Δ < 2 %

Example

ORC mass flow & evaporation pressure



SSD application

2. R-test

$$R = \frac{s_1^2}{s_2^2} < R_{critical}$$

$$s_2^2 = \frac{\delta_{f,i}^2}{2}$$

$$s_1^2 = \frac{(2-\lambda_1)\, v_{f,i}^2}{2}$$

$$v_{f,i}^2 = \lambda_2 (x_i - x_{f,i-1})^2 + (1-\lambda_2)\, v_{f,i-1}^2$$

$$x_{f,i} = \lambda_1 x_i + (1-\lambda_1)\, x_{f,i-1}$$

$$\delta_{f,i}^2 = \lambda_3 (x_i - x_{i-1})^2 + (1-\lambda_3)\, \delta_{f,i-1}^2$$

- $R_{critical}$ depends on several factors, and needs to be evaluated experimentally
- Only two variables need to be storage for calculation

→ **Suitable for real time implementation**

Cao, Songling, and R. Russell Rhinehart. "An efficient method for on-line identification of steady state." Journal of Process Control 5.6 (1995): 363-374.

TEST CAMPAIGN – Input parameters

1 Hz frequency acquisition

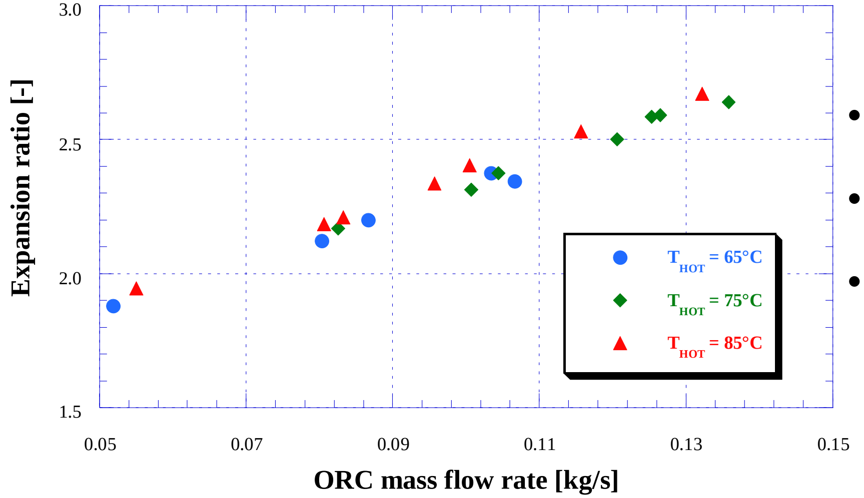
Measured data averaged on steady -state time windows

Set points		**Ranges of measured input data**						
T_{HOT} [°C]	n_{pump} [rpm] (min-max)	$\dot{V}_{HOT}$ [l/s]	T_{COLD} [°C]	$\dot{V}_{COLD}$ [l/s]	$\dot{m}_{ORC}$ [kg/s] (min-max)	p_2 [bar] (min-max)	p_3 [bar] (min-max)	$\dot{Q}_{in}$ [kW] (min-max)
65	**270-450**	2.60	17.5	2.80	0.052-0.103	10.9-14.4	5.8-6.1	10.4-20.3
75	**375-600**	2.60	18.0	2.80	0.083-0.136	13.0-16.9	6.0-6.4	16.1-25.8
85	**270-600**	2.60	17.3	2.80	0.055-0.132	11.0-16.8	5.7-6.3	11.7-25.4

- **TESTS PERFORMED AT THREE HOT WATER TEMPERATURE SET POINTS**
- **ORC PUMP SPEED VARIED BY RISING STEPS**
- **HOT AND COLD WATER FLOW RATES KEPT CONSTANT**

TEST CAMPAIGN – Experimental results

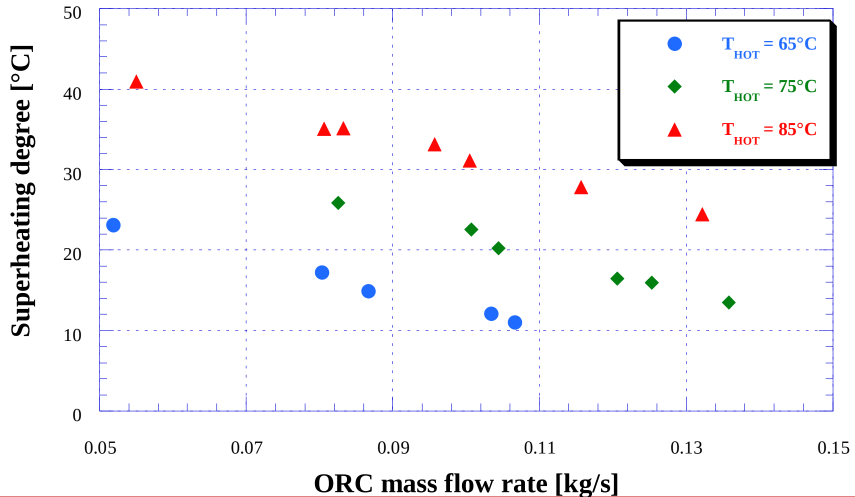
EXPANSION RATIO VS. MASS FLOW RATE



Operating conditions

- Maximum evaporation pressure ≅ 17 bar
- Condensation pressure keeps constant ≅ $6\ bar$
- Expansion ratio not influenced by hot water temperature

SH DEGREE VS. MASS FLOW RATE



Superheating degree depending on mass flow rate and T_{HOT}

$$\Delta T_{SH} = T_{SH} - T_{SAT}(p_{ev})$$

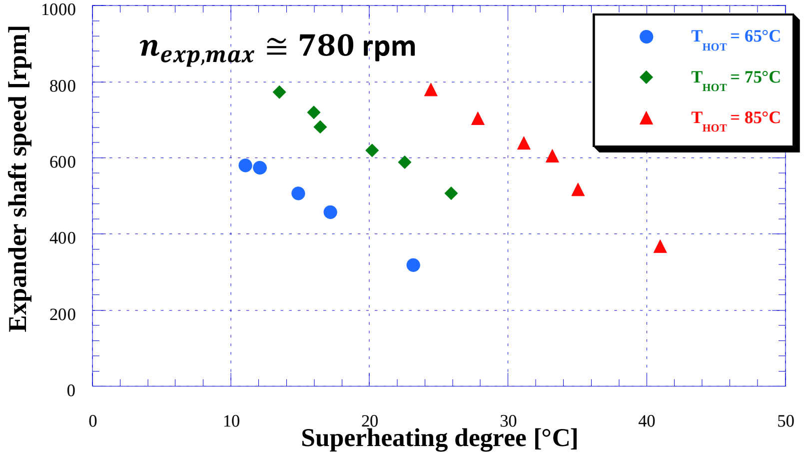
$$T_{SH} \cong T_{HOT}$$

Performance parameters expressed as function of ΔT_{SH}

TEST CAMPAIGN – Experimental results

Expander performances

EXP. SHAFT SPEED VS. SH DEGREE

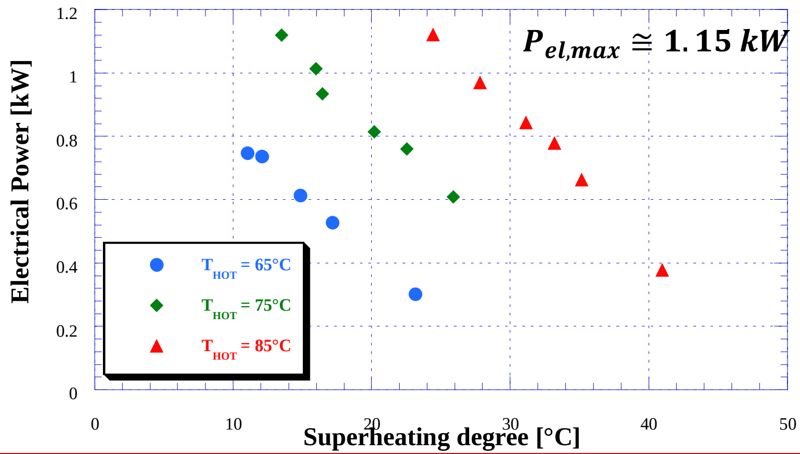


- Electric power measured at generator
- Shaft speed obtained by electrical frequency
- Isentropic efficiency

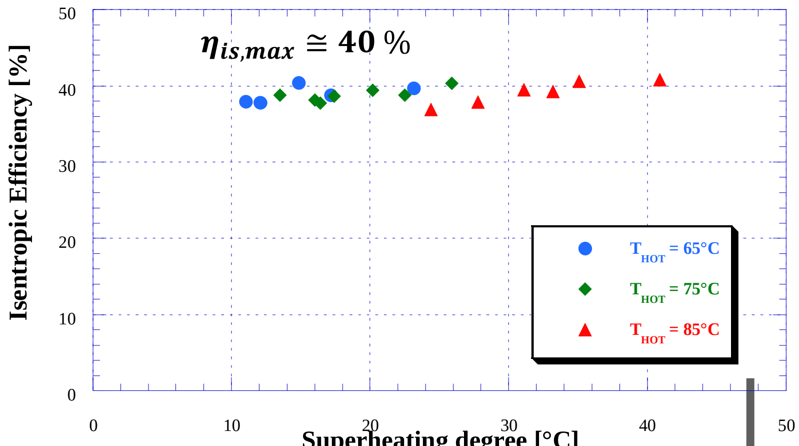
$$\eta_{is,el} = \frac{P_{el}}{\dot{m}_{ORC} \cdot (h_{in} - h_{out\ is})_{exp}}$$

not significantly affected by load variations

EL. POWER OUTPUT VS. SH DEGREE



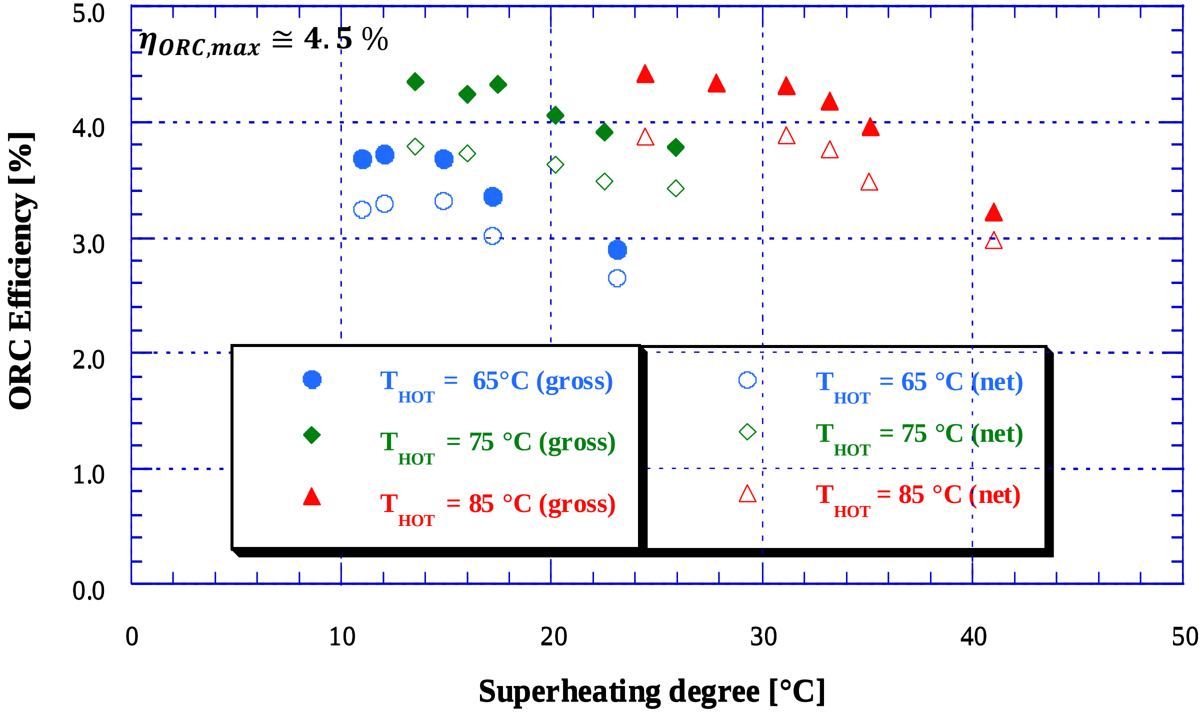
ISENTROPIC EFFICIENCY VS. SH DEGREE



TEST CAMPAIGN – Experimental results

Total efficiency

ORC EFFICIENCY



$$\eta_{ORC,gross} = \frac{P_{el}}{\dot{Q}_{ev}}$$

Net efficiency calculated subtracting feed pump hydraulic power

$$\eta_{ORC,net} = \frac{P_{el} - P_{pump,hyd}}{\dot{Q}_{ev}}$$

From literature on micro-ORC test bench:

$$\eta_{pump} = \frac{P_{pump,hyd}}{P_{pump,el}} = 20 \div 50 \text{ \%}$$

Real pump consumption deeply influences overall efficiency and needs to be accurately measured

CONCLUSION

- Experimental analysis on a micro-ORC energy system, driven by a prototypal three cylinders reciprocating expander
- Test bench implemented with water supply circuits and real-time acquisition system
- Test campaign conducted at steady state conditions, at different hot source temperature set points (65 °C - 75 °C - 85 °C), and varying feed pump speed
- Experimental results show a maximum power output of 1.15 kW_{el} at 780 rpm, for expansion ratio close to 2.7, decreasing with superheating degree
- Expander isentropic efficiency close to 40 %, not significantly influenced by operating conditions
- Maximum ORC efficiency ≅ 4.5 % (auxiliary consumption not included)

FUTURE STEPS

- Full characterization of system behavior, investigating more operating conditions
- Acquisition of electrical pump and frequency drive consumption, in order to determine the impact of auxiliaries on system efficiency
- Real-time implementation of steady state detection algorithm R-test
- Evaluation of thermal losses through expander walls

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