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

FCT Fundação para a Ciência e a Tecnologia
MINISTÉRIO DA CIÊNCIA, TECNOLOGIA E ENSINO SUPERIOR
laeta laboratório associado
ADAI
U C
FCTUC FACULDADE DE CIÊNCIAS E TECNOLOGIA UNIVERSIDADE DE COIMBRA
UC DEM Departamento de Engenharia Mecânica

DEVELOPMENT OF A DIRECT CONCEPT HELICAL-COIL EVAPORATOR FOR AN ORC BASED MICRO-CHP SYSTEM

João S. Pereira [a*], José B. Ribeiro [a], Ricardo Mendes [a], Gilberto C. Vaz [a,b], Jorge C. André [a].

[*] PhD student in Sustainable Energy System at MIT Portugal Program in University of Coimbra.
[a] ADAI-LAETA, Department of Mechanical Engineering, University of Coimbra, Pólo II, 3030 Coimbra, Portugal.
[b] Instituto Politécnico de Coimbra – Instituto Superior de Engenharia de Coimbra, 3030 Coimbra, Portugal.

ENERGIA PARA A SUSTENTABILIDADE
ENERGY FOR SUSTAINABILITY • EfS | UC
U C
MIT Portugal
MIT Massachusetts Institute of Technology

15 of September of 2017

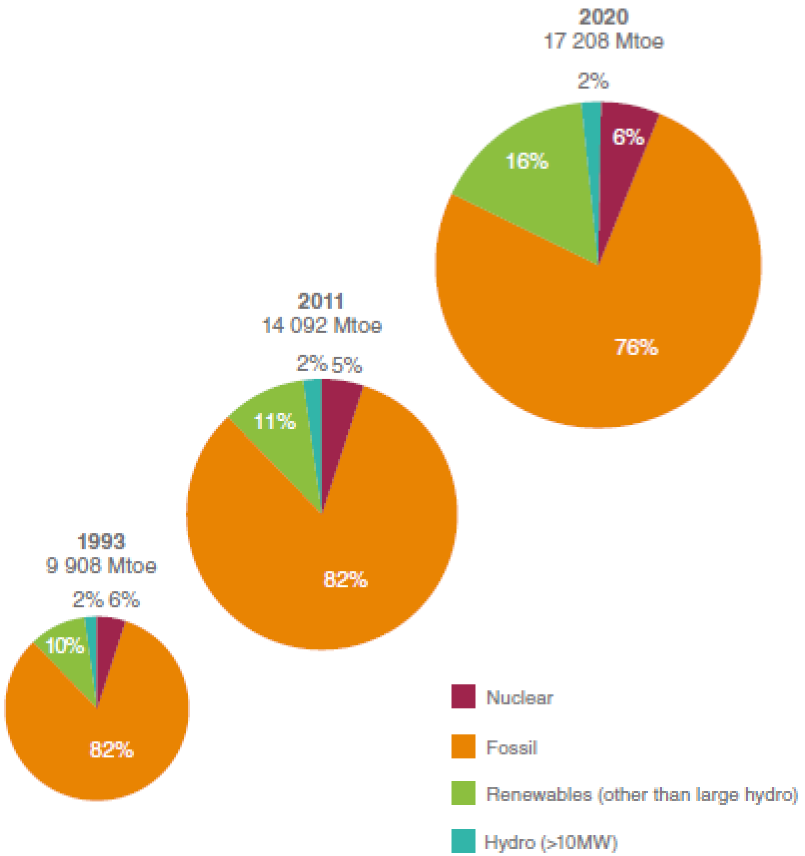
MOTIVATION

Reference: World Energy Council, *World Energy Resources - 2013 Survey*. 2013

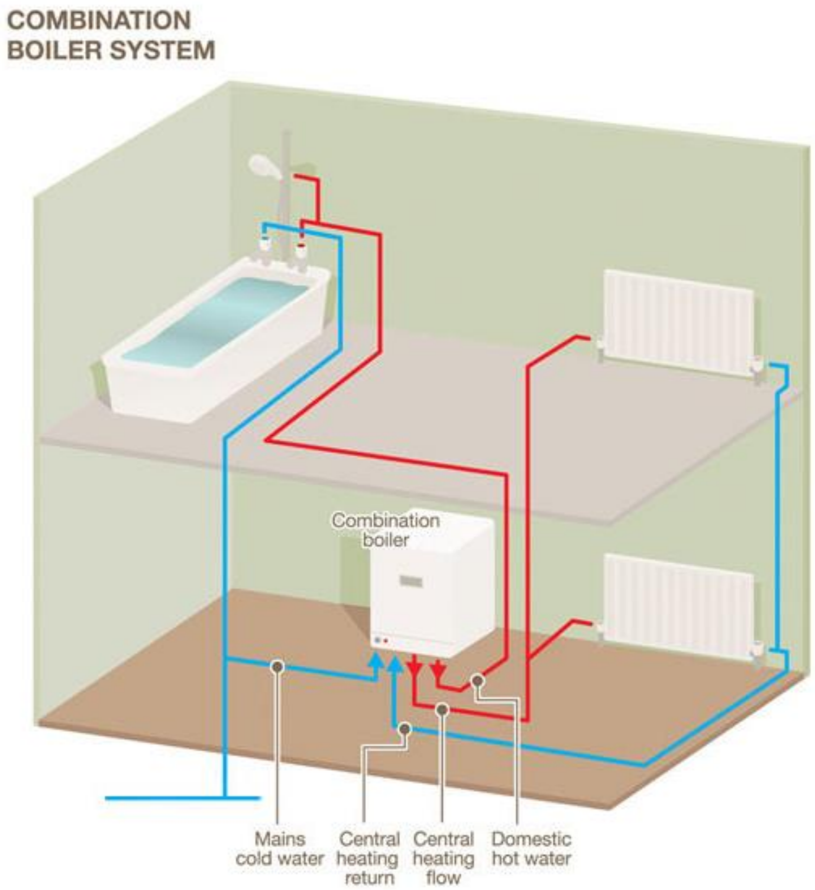
	1993	2011	2020	% growth (1993-2011)
Population [billion]	5.5	7	8.1	27%
Gross domestic product [trillion USD]	25	70	65	180%
Total primary energy demand [Mtoe*]	9 532	14 092	17 208	48%
Coal [Mt*]	4 474	7 520	10 108	68%
Oil [Mt*]	3 179	3 973	4 594	25%
Natural gas [bcm*]	2 176	3 518	4 049	62%
Nuclear [TWh*]	2 106	2 386	3 761	13%
Hydro power [TWh*]	2 286	2 767	3 826	21%
Biomass [Mtoe*]	1 036	1 277	1 323	23%
Other renewables [TWh*]	44	515	1 999	1170%
Electricity production/year				
Total [TWh*]	12 607	22 202	23 000	76%
Per capita [MWh*]	2	3	3	52%
CO_2 emissions/year				
Total CO_2 [Gt*]	21	30	42	44%
Per capita [tonne CO_2]	4	4	n/a	11%

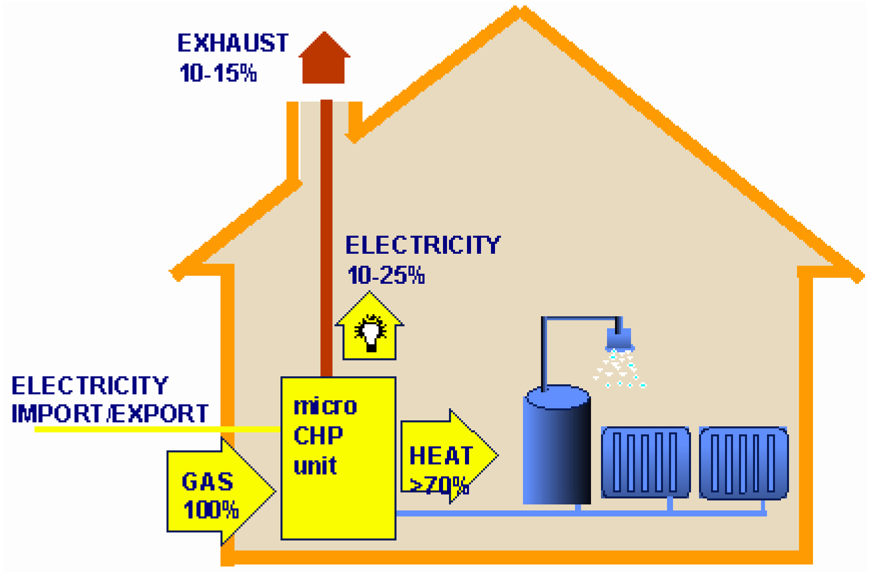
* **Mtoe** Million tonnes of oil equivalent; **Mt** Mega tonne; **Gt** Giga tonne; **bcm** Billion of cubic meters; **TWh** Tera Watt hour; **MWh** Mega Watt hour;

Total Primary Energy Supply by resource

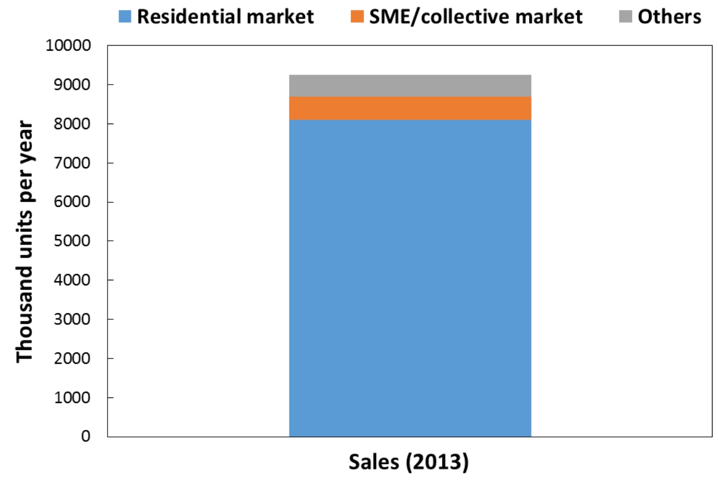


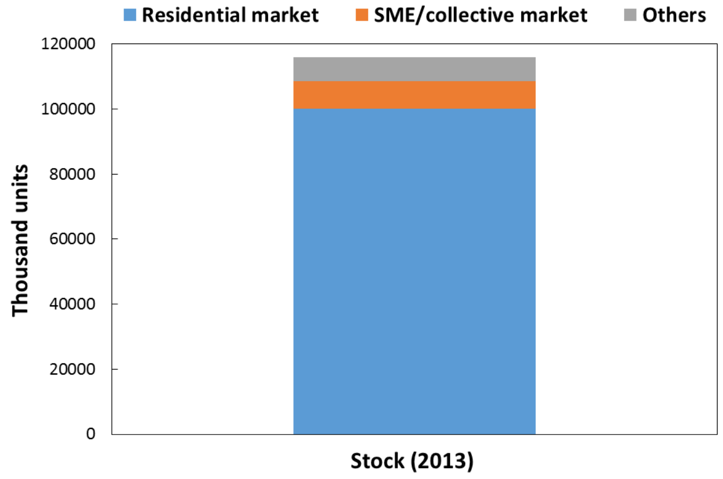
HEBE PROJECT





HEBE POTENTIAL IN THE EU-27





Reference: CODE 2 - Cogeneration Observatory and Dissemination Europe. Micro-CHP potential analysis - European level report. 2014

Residential systems (± 1 kW_e)*		SME and Collective systems (± 40 kW_e)**	
Expected sales:	in 2020: 52 000 units/year; in 2030: 2 900 000 units/year;	Expected sales:	in 2020: 2 700 units/year; in 2030: 68 000 units/year;
Expected stock:	in 2020: 103 000 units; in 2030: 14 400 000 units; in 2040: 30 500 000 units;	Expected stock:	in 2020: 18 000 units; in 2030: 290 000 units; in 2040: 950 000 units;
Potential primary energy savings in 2030:			
300 000 TJ***/year;		240 000 TJ***/year;	
Potential GHG-emissions reduction in 2030:			
13 $MtCO_{2,eq}$***/year;		14 $MtCO_{2,eq}$***/year;	

* by replacement technology; ** by add-on technology; *** **TJ** Tera Joule; **$MtCO_{2,eq}$** Mega tonne of CO_2 equivalent;

HEBE SPONSORS

sciven

· U C ·

TÉCNICO LISBOA

activespace technologies
making space a global endeavour

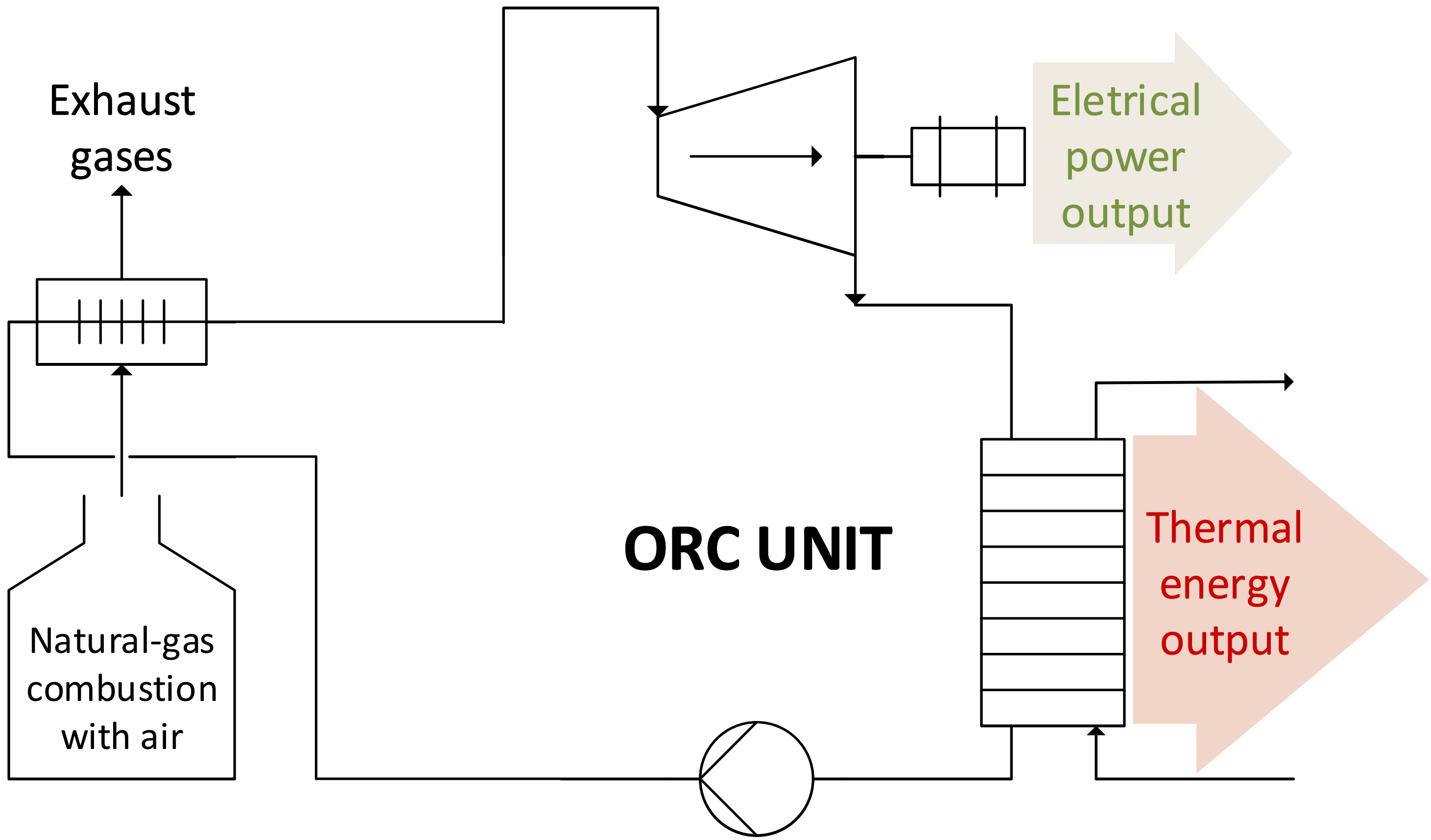
FEDER Funds through the program COMPETE: QREN-POFC-COMPETE-23101

COMPETE
PROGRAMA OPERACIONAL FACTORES DE COMPETITIVIDADE

QREN
QUADRO DE REFERÊNCIA ESTRATÉGICO NACIONAL
PORTUGAL 2007.2013

UNIÃO EUROPEIA
Fundo Europeu de Desenvolvimento Regional

SYSTEM TARGET



DIRECT EVAPORATOR DESIGN FEATURES

Size

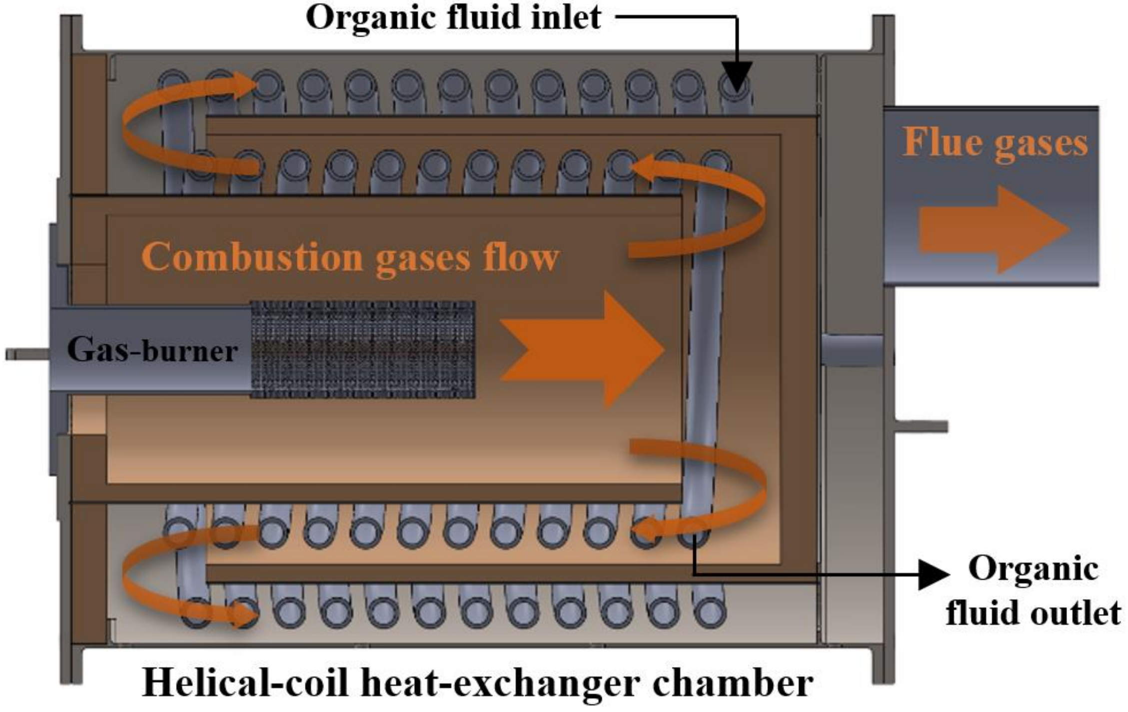
Efficiency

Power modulation capacity

Safe & reliable

EVAPORATOR PROTOTYPE

WORKING PRINCIPLE



DIRECT EVAPORATOR DESIGN FEATURES
Size
Efficiency
Power modulation capacity
Safe & reliable

EVAPORATOR PROTOTYPE

MODELING

Micro-CHP Hebe	Comercial limitations	Combustion model
Working fluid selection	Tube dimensions (D_e, D_i) and properties (k_t)	Composition of the combustion gases
Working fluid temperatures ($T_{f,in}$, $T_{f,out}$)	Burner nominal power $(\dot{Q}_c)$	Combustion gases temperatures ($T_{g,in}$, $T_{g,out}$)
Working fluid mass flow rate $(\dot{m}_f)$	Burner dimensions	Combustion gases mass flow rate $(\dot{m}_g)$
Required power $(\dot{Q}_f)$		

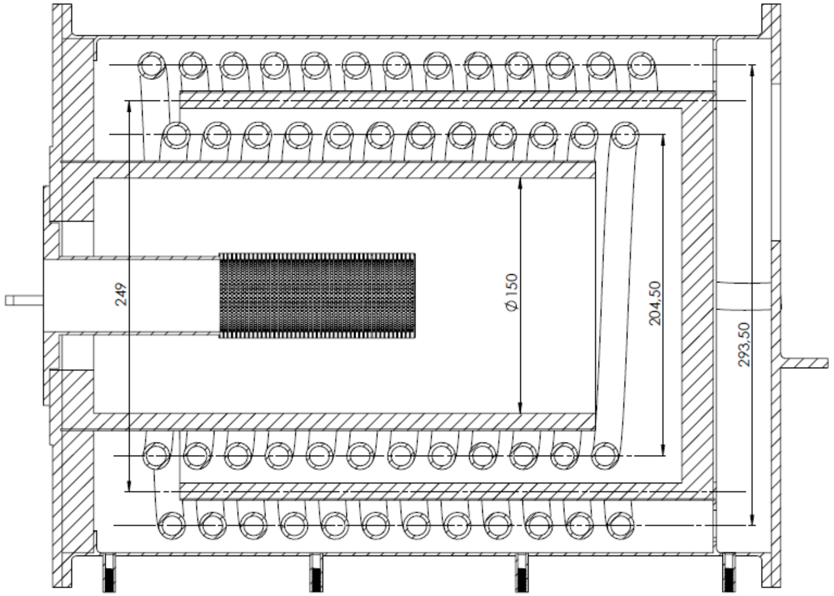
$$A_{ht}(L_t, D_e) = (\boldsymbol{NTU}, U_{ht}, C_{min})$$

→ $\mathrm{NTU}\left(\frac{Cmin}{Cmax}, \varepsilon\right)$, where $\varepsilon\left(\dot{Q}_f, \dot{Q}_c\right)$

→ $U_{ht}\ (h_h, R_w(k_t), h_c)$, where $h_x\ (Re_x, Nussel_x, k\ (T_x, p_x), D_x)$

→ $C_{min/max}\ (cp(T_x, p_x), \dot{m}_x)$

Final output: $L_t \cong 19{,}4\ [m]$ given ≅ 24 coils



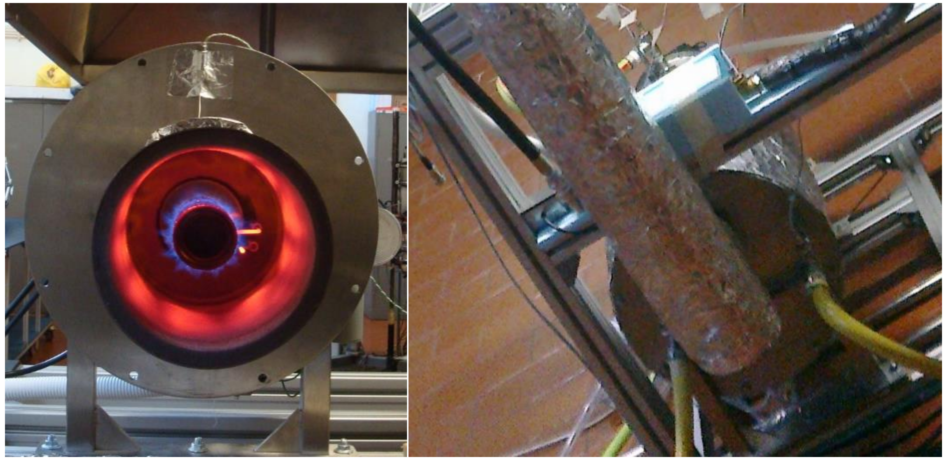
EVAPORATOR PROTOTYPE

CONSTRUCTION & ASSEMBLY

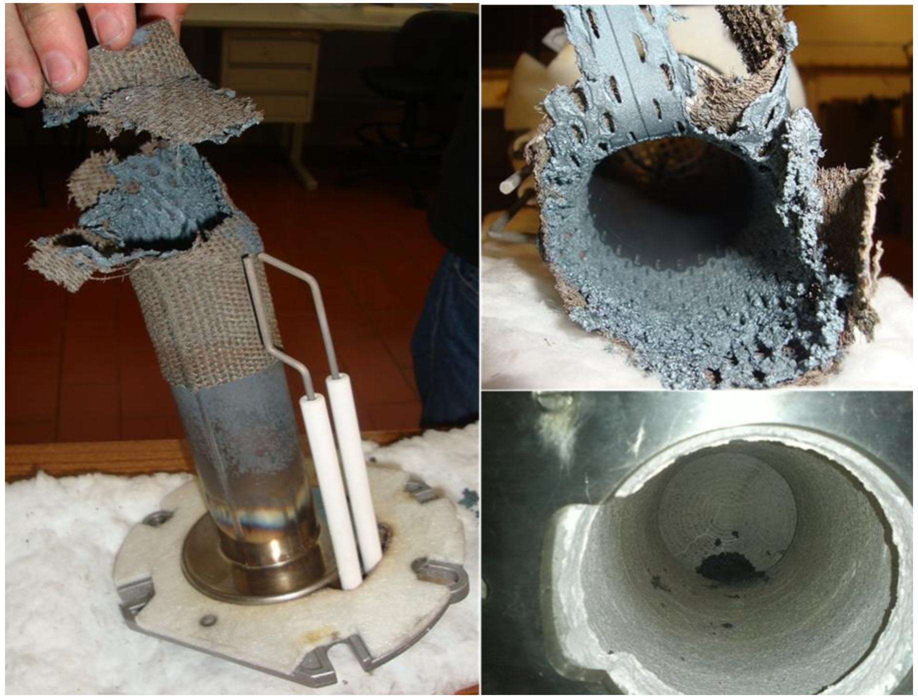
Model		RX 35 S/PV	RX 70 S/PV	RX 110 S/PV
Burner operation mode		Modulating (with variable speed)		
Modulation ratio at max. output		7 ÷ 1	8 ÷ 1	8 ÷ 1
Servo-motor	tipe	--		
Servo-motor run time	s	--		
Heat output	kW	5 - 35	9 - 70	14 - 110
	Mcal/h	4,3 - 30,1	7,7 - 60,2	12 - 94,6
Working temperature	°C min./max.	0/40		

EVAPORATOR PROTOTYPE

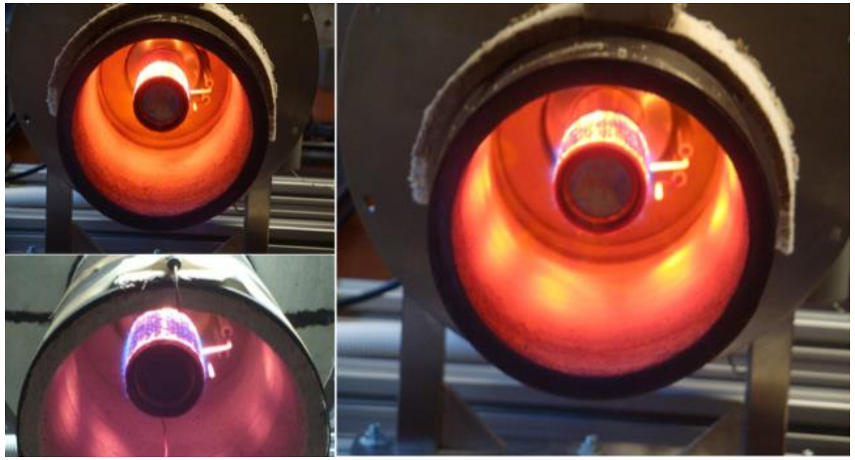
PRELIMINARY TESTS



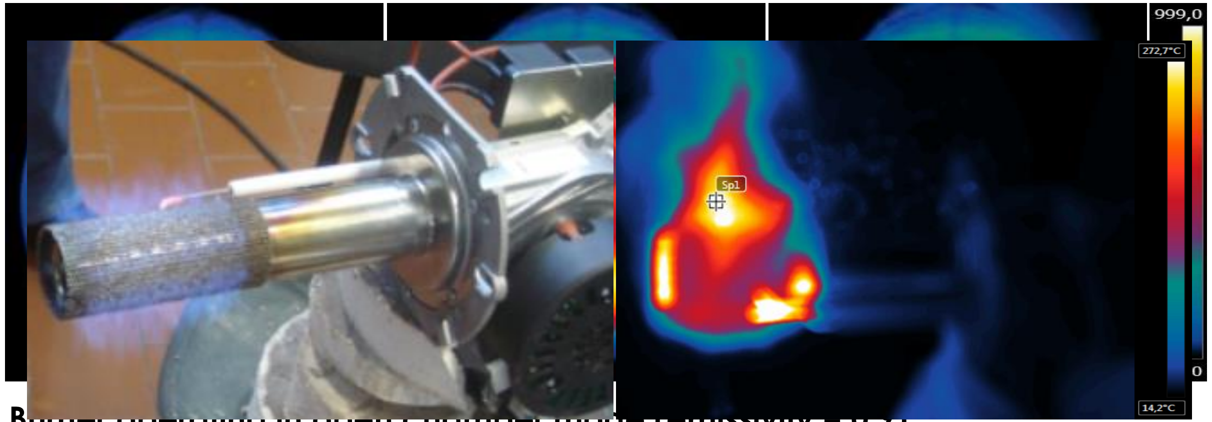
During the preliminary tests…



EVAPORATOR PROTOTYPE
ACCIDENT DIAGNOSTIC



Examples of dangerous operational situations (Burner manufacturer contact)

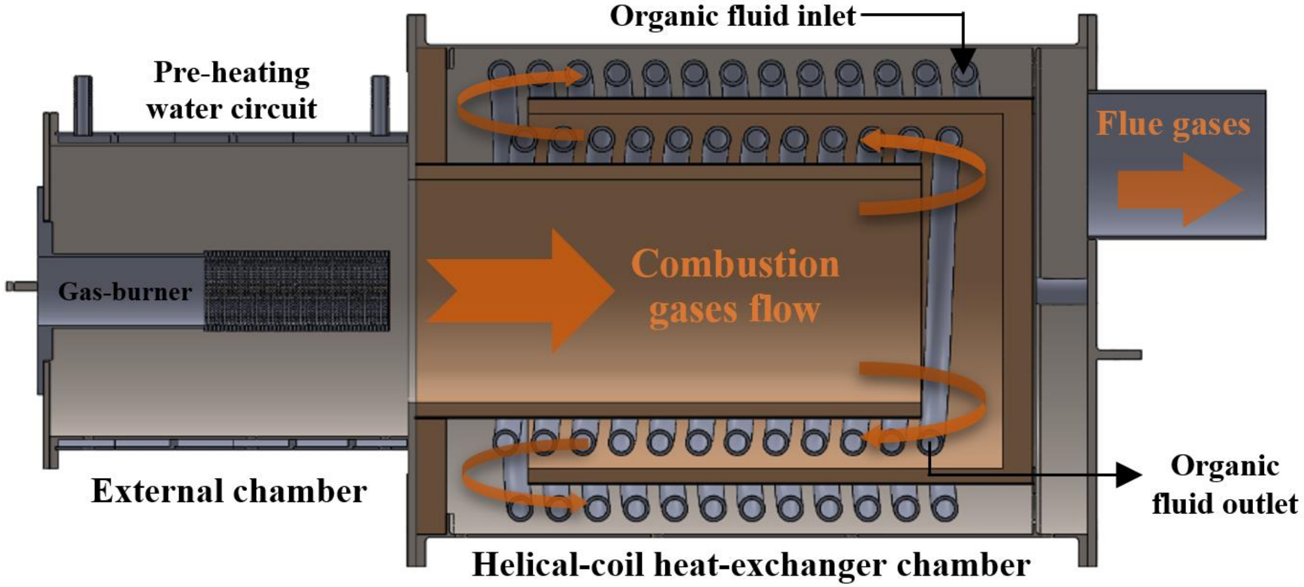


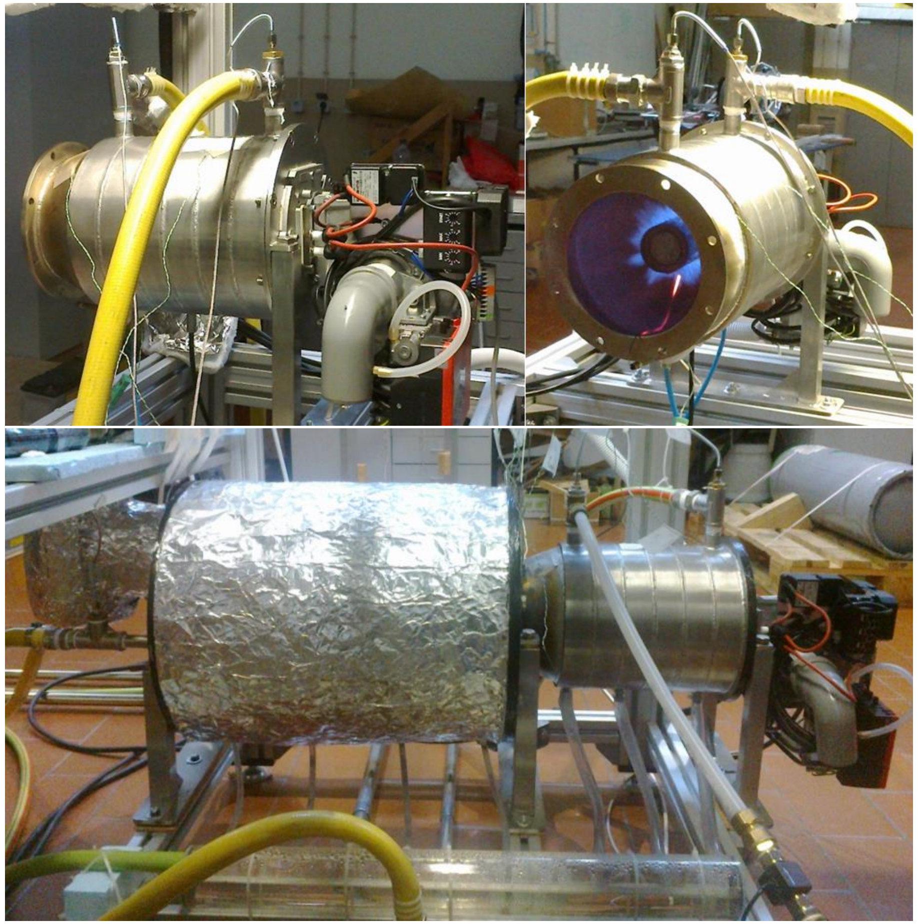
Burner operating in open chamber mode (emissivity = 0,7)
Left picture: nominal power of 30% (Sp1 = 789.1 °C and Sp2 = 958.1 °C);
Middle picture: nominal power of 30% (Sp1 = 827.2 °C and Sp2 = 1006 °C);
Right picture: nominal power of 70% (Sp1 = 861.2 °C and Sp2 = 1025.2 °C).

Burner operation without surrounding (emissivity = 0.9):
Left picture: nominal power of 50% – regular picture;
Right picture: nominal power of 50% – thermal picture (Sp1 = 267.8 °C).

EVAPORATOR PROTOTYPE

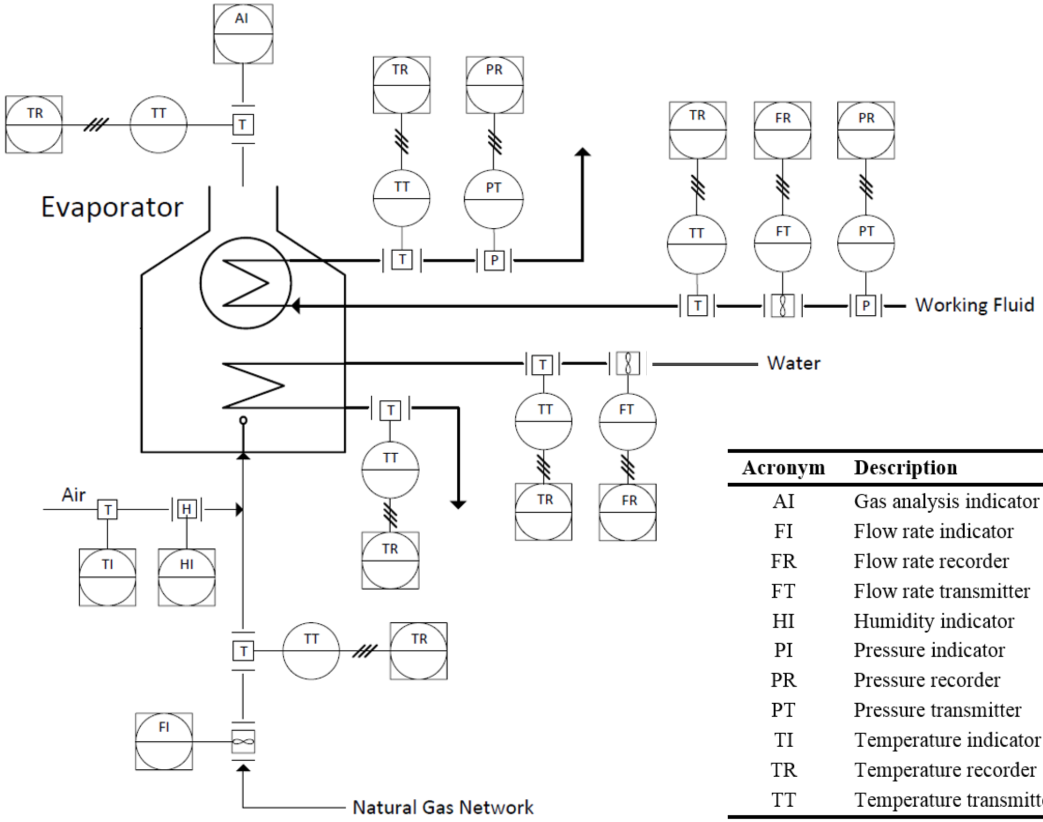
REDESIGNED WORKING PRINCIPLE AND SAFETY OPERATIONAL TESTS





EVAPORATOR PROTOTYPE

THERMAL CHARACTERIZATION: TEST BENCH



Acronym	Description
AI	Gas analysis indicator
FI	Flow rate indicator
FR	Flow rate recorder
FT	Flow rate transmitter
HI	Humidity indicator
PI	Pressure indicator
PR	Pressure recorder
PT	Pressure transmitter
TI	Temperature indicator
TR	Temperature recorder
TT	Temperature transmitter

Measured parameters	Sensor-type	Operation limits	Uncertainty
Working fluid and water flow rate	Vane turbine flowmeter (infra-red sensor)	max. 20 bar; max. 25 L/min; max. 70 ºC	+- 2%
Water and natural gas temperature	RTD PT100	-50 to 500 ºC	B class
Working fluid, flue gases and air temperature	Thermocouple type 'K'	-40 to 1100 °C	+- 0.75%
Air humidity	External capacitive sensor	0 to 100%	+- 2,5%
Working fluid pressure	Relative pressure transducers	0 to 25 bar; -40 to 149 °C	0.25% FS
Natural gas flow rate	Diaphragm gas meter	0 to 1,5 bar; -25 to 55°C	Class 1.5 - by EN 1359
Combustion products	Dry flue gas analyser with non-dispersive infrared sensor for O_2, CO_2, CO	O_2: 0 to 25%; CO_2: 0 to 20%; CO: 0 to 10%	O_2: 0.01%; CO_2: 0.02%; CO: 0.1%

EVAPORATOR PROTOTYPE

THERMAL CHARACTERIZATION: METHODOLOGY

Stage 1: With water as working fluid (in a open circuit):

- Burner capacity: 10%, 20%, 40%, 50%, 70%, 90% and 100%;
- Working fluid mass flow rate: 0,1 kg/s, 0,15 kg/s and 0,2 kg/s;
- Water (CW) mass flow rate: 0,1 kg/s;
- Time: 300 seconds.

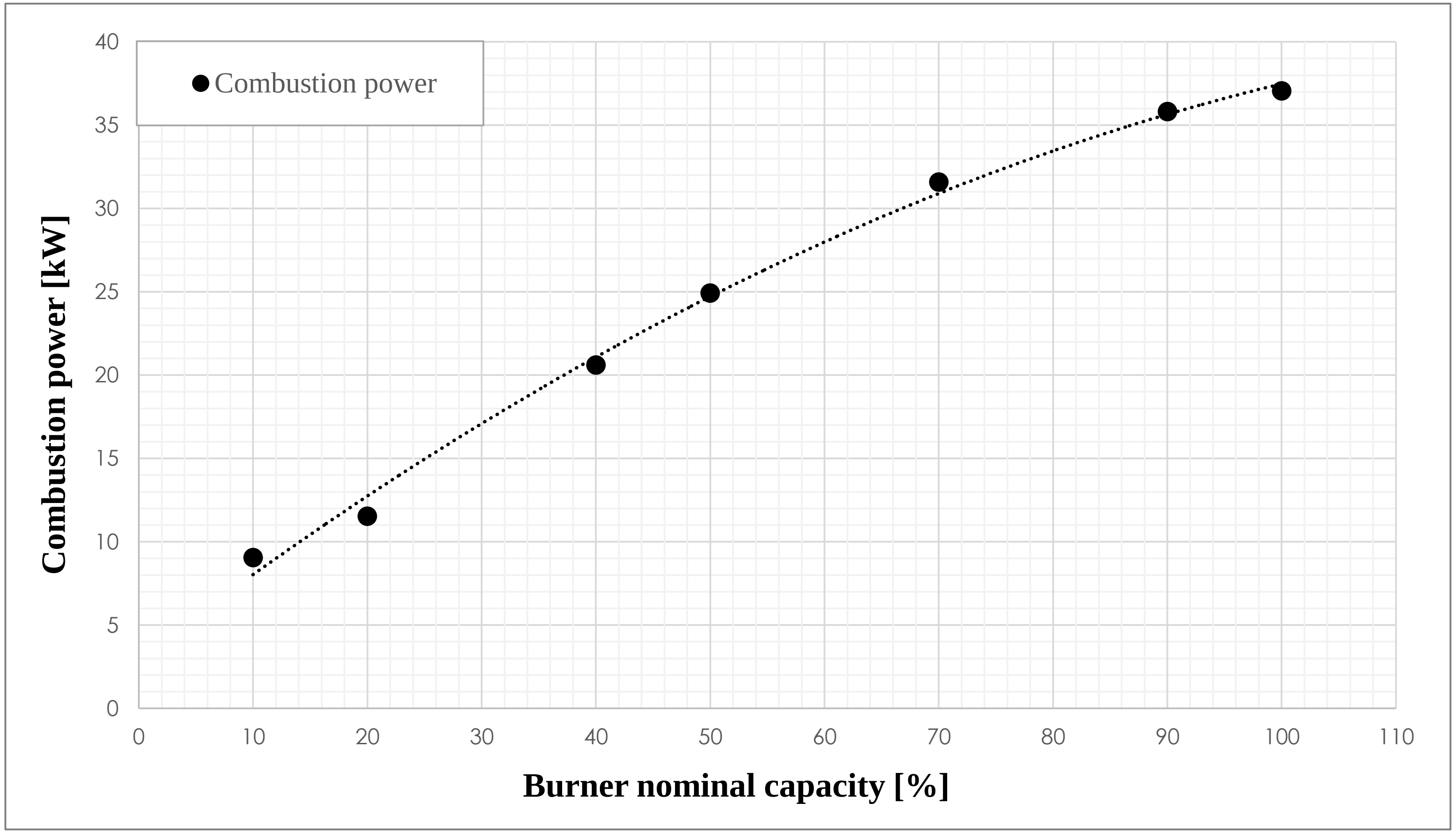
Stage 2: With R245fa (HEBE micro-CHP system integrated):

- Burner capacity: 17%, 22%, 25% and 30%;
- Working fluid mass flow rate: adjusted on-site (P1 rotation);
- Water mass flow rate: 0,1 kg/s;
- Time: 300 seconds.

Variable objective [unit]	Mathematical equation
Combustion power [kW]	$\dot{Q}_{comb} = \sum_P \left(\dot{n} \times \bar{h}_f^o\right)_P - \sum_R \left(\dot{n} \times \bar{h}_f^o\right)_R$
Pre-heating water power [kW]	$\dot{Q}_w = \dot{m}_w \times cp_w \times \Delta T_w$
Working fluid power [kW]	$\dot{Q}_f = \dot{m}_f \times \Delta h_f$
Flue losses [kW]	$\dot{Q}_{flue} = \sum \left(\dot{n}_P \times \Delta \bar{h}_P\right)$
Other losses [kW]	$\dot{Q}_{loss} = \dot{Q}_{comb} - \dot{Q}_w - \dot{Q}_f - \dot{Q}_{flue}$
Global efficiency [%]	$\eta_{global} = (\dot{Q}_f + \dot{Q}_w)/\dot{Q}_{comb}$

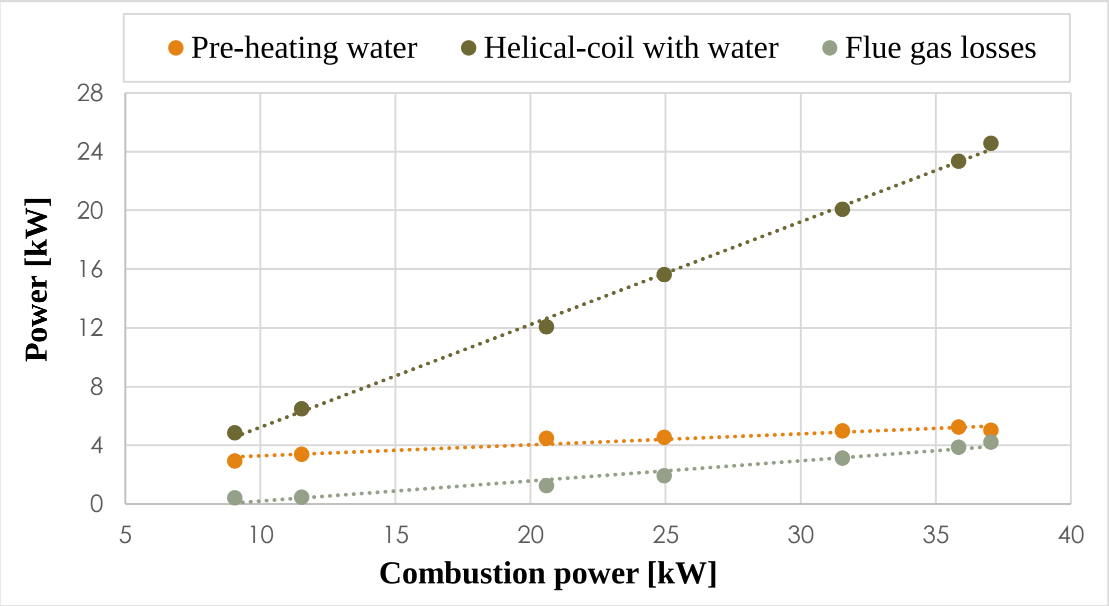
EVAPORATOR PROTOTYPE

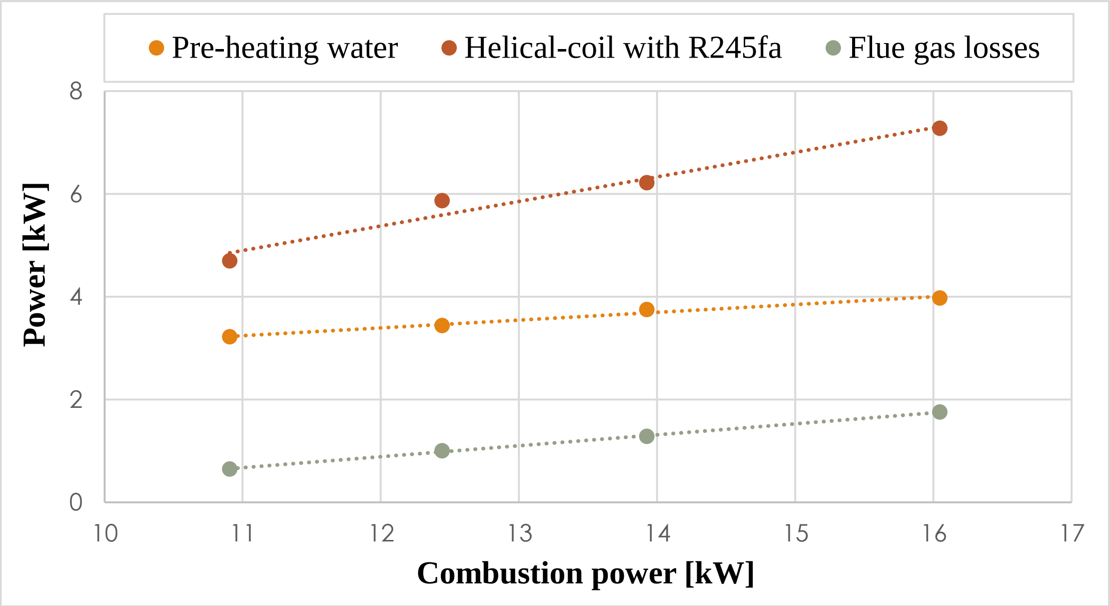
THERMAL CHARACTERIZATION: RESULTS



EVAPORATOR PROTOTYPE

THERMAL CHARACTERIZATION: RESULTS

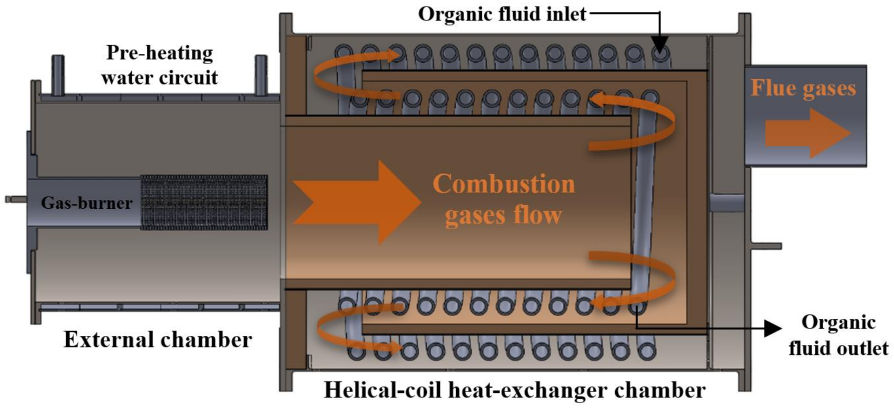




Burner capacity [%]	**10**	**20**	**40**	**50**	**70**	**90**	**100**
Combustion power [kW]	9.053	11.532	20.598	24.952	31.557	35.855	37.053
Water power [kW]	3.064	3.383	4.473	4.524	4.967	5.224	5.016
Working fluid power [kW]	5.134	6.594	12.063	15.61	20.06	23.345	24.565
Flue losses [kW]	0.412	0.447	1.248	1.923	3.106	3.864	4.206
Other losses [kW]	0.443	1.108	2.814	2.895	3.424	3.422	3.266
Global efficiency [%]	90.6	86.52	80.28	80.69	79.31	79.68	79.83

Burner capacity [%]	**17**	**22**	**25**	**30**
Combustion power [kW]	10.907	12.445	13.928	16.047
Water power [kW]	3.218	3.538	3.747	3.974
Working fluid power [kW]	4.695	5.864	6.213	7.275
Flue losses [kW]	0.646	1.001	1.28	1.756
Other losses [kW]	2.348	2.266	2.688	3.042
Global efficiency [%]	72.55	75.55	71.51	70.1

EVAPORATOR PROTOTYPE
CONCLUSIONS & FUTURE WORK



- A burner heat-exchanger set was built to perform the direct vaporization of the organic fluid of an ORC system.
- Fulfill safety and control requests;
- The heating transfer coefficient of the external flow needs to be optimized;
- The external chamber appears to have very potential:
  1. Preclude the overheating of the gas-burner head;
  2. Increasing the ORC efficiency by pre/post heating the end user water;
  3. Decreasing the combustion gas temperature before reaching the organic fluid, reducing the risk of thermal degradation;

THANK YOU FOR YOUR ATTENTION

João Silva Pereira
(joao.pereira@dem.uc.pt)