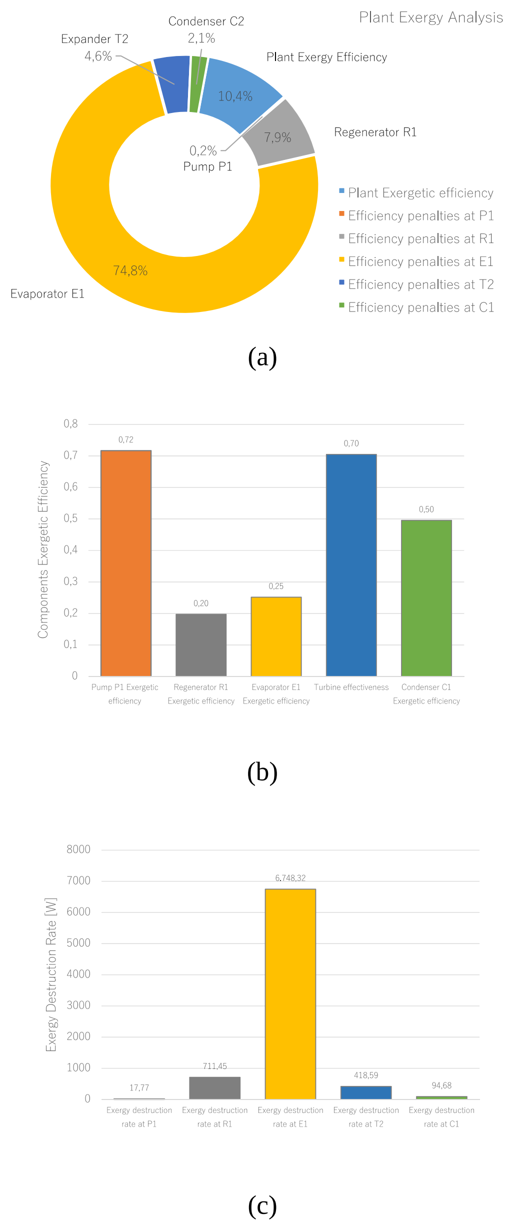

Figure 6. Main exergy analysis results: efficiency penalties distribution (a); components exergy efficiency (b); exergy destruction rate at various plant section (c)

At the condenser, exergy is transferred from the working fluid to condensing water that provide to its final destruction in the subsequent heat transfer towards the environment. The evaluated plant exergy efficiency was about 10.4%, i.e. only 10.4% of the entering plant exergy was useful converted to mechanical work.

A trace of some experimental signals acquired during tests at main plant sections (i.e. expander inlet, regenerator hot side outlet, condenser outlet), is shows in Figure 7 respectively for temperature (a) and pressure (b).

Notable is the increasing in pressure drop at the regenerator hot side that limit the pressure drop available for the expansion at the expander T2. This is largely due at the increased mass flow rate evolving inside the cycle (from about 0.023 kg/s at maximum pressure of 6 bar to 0.048 kg/s at pressure of 12 bar).

Main experimental results by data acquisition elaborations are collected at increasing maximum pressure cycle in TABLE 2 by keeping constant the temperature at the expander inlet and the condensing temperature. Experiments confirm numerical predictions: efficiency increases as pressure increases. Furthermore, good agreement between experimental data and theoretical ones was observed (Table 3): maximum efficiency registered was 8.4% at maximum inlet pressure at the expander of 10 bar. The deviation by theoretical data is in all cases evaluated below 4%.

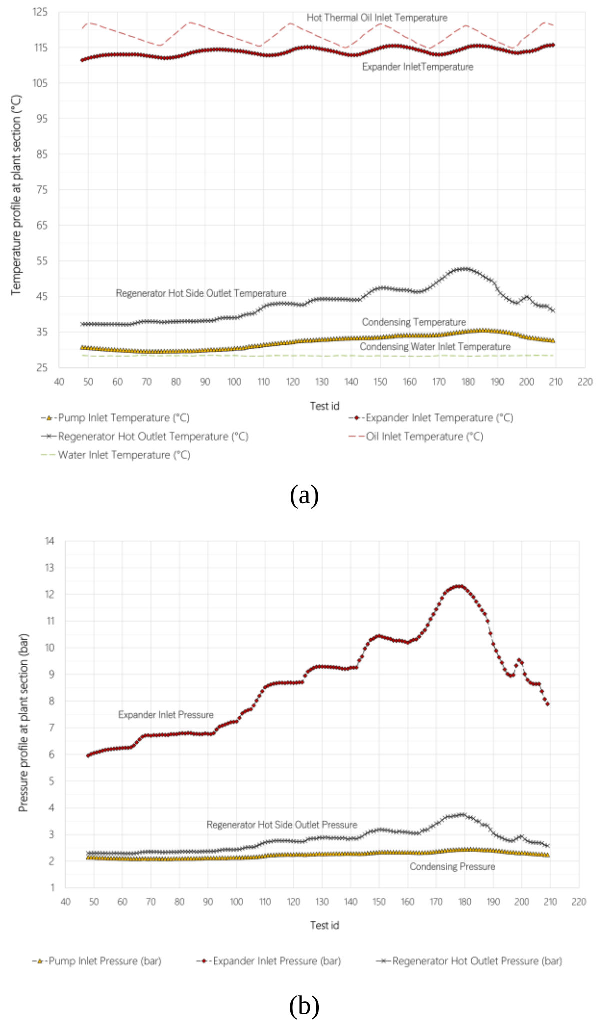

Figure 7. Some experimental data acquired during tests at the ORCLab: temperature (a) and pressure profiles (b) at the main plant sections (i.e. expander inlet, regenerator hot side outlet, condenser outlet)

Table 2. Main experimental results extracted by acquired data during tests at the ENEA's ORCLab operated in regenerative mode

Reference pressure at inlet expander section	**8 bar**	**9 bar**	**10 bar**
Thermodynamic properties	Experimental Data		
p_1 Inlet pump pressure (bar)	2.16	2.25	2.29
P_2 Outlet pump pressure (bar)	8.67	9.59	10.87
p_5 Inlet expander pressure (bar)	8.02	8.95	9.97
$p_{6'}$ Outlet expander pressure (bar)	3.62	3.67	3.77
T_1 Inlet pump temperature (°C)	31.07	32.63	33.38
T_2 Oulet pump temperature (°C)	31.40	33.04	34.10
$T_{2'}$ Inlet evaporator temperature (°C)	68.69	70.46	71.90
T_5 Inlet expander temperature (°C)	113.32	115.04	113.63
$T_{6'}$ Outlet expander temperature (°C)	91.93	92.77	92.94
T_6 Inlet condenser temperature (°C)	40.36	42.68	43.14
First law efficiency	7.63%	7.91%	8.43%

Table 3. Theoretical vs. experimental data comparison of main results obtained respectively by the mathematical model and acquired during tests at the ORCLab facility operated in regenerative mode

Test pressure	8 bar		9 bar		10 bar	
Th. Properties	Th.	Exp.	Th.	Exp.	Th.	Exp.
p_5 (bar)	8.0	8.0	8.9	8.9	10.0	10.0
T_5 (°C)	113.2	113.2	115.1	115.1	113.6	113.6
$T_{6'}$ (°C)	89.4	91.9	88.8	92.8	83.6	92.9
p_1 (bar)	1.8	2.2	1.9	2.3	2.0	2.3
Efficiency (%)	7.6	7.6	8.1	7.9	8.8	8.4

Notes: p_5 and T_5 pressure and temperature at expander inlet section. $T_{6'}$ temperature at expander outlet section. p_1 pressure at pump inlet (i.e. pressure of condensation).

5. CONCLUSIONS

In this study, a small Organic Rankine Cycle utility (ORCLab - 1 kW_e) for low grade heat recovery was tested by using R245fa as working fluid. In order to increase the overall plant efficiency, the equipment was tested in regenerative mode by imposing the maximum temperature at the expander inlet (115°C) and the electrical load at the generator (i.e. by inducing a variation in the maximum cycle pressure up to 13 bar). Rotational speed was kept constant (3600 RPM) by controlling the working fluid mass flow rate evolving inside the cycle. A first approach thermodynamic model was also developed to predict the performances of the ORC, and main results were discussed in some details. Exergy analysis was also performed to locate main irreversibilities inside the thermodynamic cycle. It was found that about 75% of the entering exergy was destroyed at the evaporator E1. This means that only the residual 25% can be potentially converted in useful work. The evaluated plant exergy efficiency was 10.4%, not low if compared to the ideal Carnot efficiency of a thermodynamic cycle evolving between the same extreme temperature (about 21%). By elaborations of the acquired experimental data, the maximum first law efficiency was 8.43% at maximum cycle pressure of 10 bar and at maximum inlet temperature at the expander of 115°C. Good agreement between theoretical and experimental data was also observed: the maximum deviation was in all cases investigated below 4%.

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NOMENCLATURE

$\dot{E}_d$	Exergy destruction rate [W]
e	Specific exergy [kJ/kg]
g	Gravitational acceleration [m/s^2]
h	Specific enthalpy [kJ/kg]
$\dot{m}$	Mass flow rate [kg/s]
p	Pressure [Pa]
s	Specific entropy [kJ/kg K]
T	Temperature [K]
u	Specific internal energy [kJ/kg]
v	Specific volume [m^3/kg]
$\dot{W}_{cv}$	Net power transferred on the control volume [W]
w	Velocity [m/s]
z	Altitude [m]

Greek symbols

η	Efficiency
ε_{ex}	Exergy efficiency

Subscripts

c	Cold
C1	Condenser C1
e	exit
h	Hot
i	inlet
E1	Evaporator E1
o	Outlet

oil	Thermal oil	T2	Expander T2
P1	Pump P1	w	water
R1	Regenerator R1	wf	working fluid