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Performance and operation of micro-ORC energy system using geothermal heat source

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Abstract

In the electricity production sector, geothermal energy is considered a reliable energy source because of its independence of seasonal, climatic and geographical conditions. Low-temperature geothermal wells present a huge potential of exploitation, as the development of binary cycles and the technological improvement in drilling make this heat source a competitive solution for electricity generated distribution and self-consumption. The Organic Rankine Cycle (ORC) is currently the best solution to convert heat into electricity using low enthalpy heat sources. The ORC technology is already mature and widespread for medium and large-scale power plants, applying for geothermal, solar, biomass or waste heat recovery exploitation. Micro-scale ORC applications are still not diffused in the market: the system layout, the working fluid selection and the expander architecture can significantly vary depending on the specific realization requirements, thus a standard configuration has not established yet.

In this paper, a particular case study of a micro-ORC power system using a geothermal well is presented. The application in analysis is a plug-and-play ORC facility, currently installed and operating in a pool centre. The system layout and the main components are described. The heat source is a geothermal well, which continuously supplies (by pressure difference) liquid water at a temperature lower than 60 °C to a binary Rankine cycle working with R134a. The ORC system is driven by a prototypal radial-piston expander and adopts an external-gear feed pump and a recuperative cycle. It is developed for working continuously, delivering the generated electricity directly into the grid. The facility is provided with temperature, pressure and electric power sensors for monitoring the operation and for a preliminary evaluation of the performance. The global efficiency of expander and feed pump and the ORC net efficiency have been evaluated at the regular working conditions of the geothermal well, showing values equal to, respectively, 53 %, 41 % and 4.4 %.

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1. Introduction

Geothermal source exploitation has been growing in the last decades, as the power installed worldwide almost doubled between 1995 and 2015, with a total installed capacity currently close to 13 GW [1]. The use of geothermal energy indeed, significantly reduces the emission of greenhouse gases and air pollutants, in addition to lowering the consumption of fossil fuels. Considering the huge global amount of geothermal resources and the modest portion already employed for heat and electricity production, the development of new and optimized systems for converting low grade thermal power has great potential. Geothermal resources can be classified by the reservoir fluid temperature level: high temperature reservoirs (T > 240 °C) are the most appropriate for electricity generation in industrial scale, using the geothermal superheated vapour as working fluid to be expanded in the power turbine [2]. These plants can be single or double flash cycles, or dry-steam, whether the reservoir is liquid or vapour dominated. Medium and low grade geothermal power can be also recovered with binary cycles, with the further advantages of eliminating the already low emissions and preventing damages to the turbine or to heat exchangers due to the impurities contained within the geothermal water.

The Organic Rankine Cycle (ORC) has demonstrated to be the best solution for converting low temperature heat sources in small scale power plant [3]. However, the small temperature difference between the hot source and the cold sink of the cycle reduces the efficiency of such systems, comparing to traditional generation processes. The performance achievable by an ORC system depend on several factors, including the temperature levels of the external sources, the selection of the working fluid, the choice of the expansion machine and of the feed pump [4]. Focusing on the expander selection, for systems with power output lower than 150 kW, the adoption of positive displacement machines is usually preferable, due to the lower flow rates, the higher expansion ratio and the much lower rotating speed than turbines. Most applied models are the scroll, the piston, the twin-screw and the vane expanders [5]. Systems with an electric output lower than 20 kW, suitable for residential or small industry applications, are not frequent in the market to the authors' knowledge. Some installations have been realized by the French company Enogia, which commercializes units of 10 kW and 20 kW, running with R245fa and suitable for heat source temperature between 80 °C and 120 °C. They adopt turbo-generators of a new design, declaring a cycle efficiency ranging between 5 % and 8 %, depending on the hot source and cold sink conditions [6]. Also the American company Electratherm is a specialist in small scale ORC system. The smallest product they propose is an ORC unit suitable for heat source temperature between 77 °C and 116 °C. It is rated for power output up to 35 kW, running with twin-screw expander and R245fa as working fluid [7]. Other companies are Zuccato [8], with a smallest unit of 30 kW driven by radial turbine and performing an 8.5 % of cycle efficiency, Infinity Turbine [9], that develops radial outflow turbines for micro-size ORC (1-5 kW), and Orcan Energy [10], specialized in waste heat recovery with a power output between 20 kW and 100 kW.

This study is part of a collaboration of the University of Bologna with the company StarEngine Srl, which designed and developed an ORC facility currently operating in a pool centre, which is presented in this work. The system uses a geothermal liquid-dominated well as hot source, while the cold sink is the swimming pool heating circuit, and it is rated for an electric power output up to 11 kW. The original features of the system under investigation are the expansion machine, which is of reciprocating piston model (usually applied for high pressure ratio, due to the high built-in volume ratio) and an external gear pump, both originally manufactured by StarEngine. Both expander and pump are an upgrade of the machines already presented in other studies of the authors [11 - 12]. This paper aims to point out the effectiveness and the potential of the system presented, that demonstrated a good performance and reliability through two years of continuous operation at fixed and quasi-constant conditions.

Nomenclature

BWR	Back Work Ratio
η	Efficiency
FF	Filling Factor
h	Enthalpy
$\dot{m}$	Mass flow rate
N	Rotational speed
ORC	Organic Rankine Cycle
p	Pressure
$\dot{Q}$	Thermal power
ρ	Density
T	Temperature
SH	Superheating degree
V	Displacement
$\dot{W}$	Power

Subscripts

cond	Condensation
el	Electrical
exp	Expander
ev	Evaporation
hy	Hydraulic
is	Isentropic
m	Measured
pp	Pump
suc	Suction
tar	Target
vol	Volumetric

2. System description

2.1. Power plant layout and components

The plant is composed by four separate circuits: the heat source supply loop, an intermediate hot water closed-loop, the cold water circuit and the micro-ORC system fed with R134a, that is represented in Figure 1. The heat source supply loop consists in a geothermal well (originally drilled for oil exploration), which supplies (by pressure difference) liquid water at a barely constant temperature close to 65 °C, returning to the injection well at lower temperature after transferring thermal power to the intermediate loop. A heat exchanger is interposed between the geothermal water circuit and the hot water one, in order to avoid undesirable detritus depositions inside the ORC evaporator. The hot water is pumped to the evaporator inlet at temperature ranging between 52-56 °C with a volume flow rate of 22 m^3/h, by means of a centrifugal pump, providing a thermal power input of about 55 kW. Into the cold water circuit, a centrifugal pump circulates water at a temperature that varies between 16-23°C (depending on ambient conditions), with an average volume flow rate of 25 m^3/h.
The micro-ORC layout, shown in Figure 2, is composed by an evaporator, an expander, a condenser, a pump and a recuperator, to recover residual heat from vapour after the expansion. The evaporator, the condenser and the recuperator are three brazed-plate heat exchangers. The expander is a prototypal piston model, made of 4 radial cylinders placed at 90°, with a total displacement equal to 800 cm^3. The external surface of the expander has been thermally insulated in order to reduce the heat losses to the ambient. The expander is directly coupled with a three-phase asynchronous generator, which is rated for a nominal electric power of 11 kW. The generator is cooled by a small fraction of working fluid flow rate, extracted from the expander inlet pipe. The connection to the electrical grid is made through an inverter, which converts the generator frequency (related to the expander speed) to the electrical grid frequency. Therefore, the expander rotational speed is released from the grid frequency and it can be imposed by the user. A by-pass circuit was realized at the expander inlet, used during the cold start-up; it allows the fluid to flow into the external case of the expander by-passing the cylinders, in order to achieve the appropriate conditions of superheating at the start of the expansion, and at the same time to warm up the expander walls avoiding thermal stresses. The ORC feed pump is an external gear pump with a total displacement equal to 264 cm^3/rev, driven by a three-phase motor controlled by a frequency inverter. Between the motor and the pump, a mechanical speed reducer is interposed, with a reduction ratio of 3:1. The pump was designed with relatively high displacement for functioning at very low rotational speed, in order to minimise mechanical losses. See Table 1 for more specifics about the main components of the ORC system.

The power facility is provided with an embedded control system designed and customized by Siemens. The control system acquires the signals from the sensors, activates the by-pass valves and regulates the pump inverter. It also contains the rectifier for the electric power fed into the grid. The regulation can be handled in manual mode, in which the motor frequency is set by the user to the desired value, or in automatic mode, in which the pump speed is adjusted to reach and keep a target value of the superheating degree (which depends, at given superheating temperature, on the evaporation pressure and thus on the flow rate of the organic fluid).

Table 1. Main specifics of ORC system components

Heat exchangers	
Model	ONDA S404 brazed plate type
Average Volume	28 l (evaporator); 28 l (condenser); 20 l (recuperator)
Expander	
Architecture	4 radial pistons
Total displacement	800 cm^3/rev
Lubrication	Oil mixed with the working fluid
Generator	11 kW asynchronous three-phase generator
Feed pump	
Model	Prototype external gear pump
Total displacement	264 cm^3/rev
Lubrication	Oil mixed with the working fluid
Motor	3 kW three phase motor; speed reducer with 3:1 reduction ratio; rotating speed controlled by frequency drive

Figure 1. StarEngine micro-ORC installation at the well site

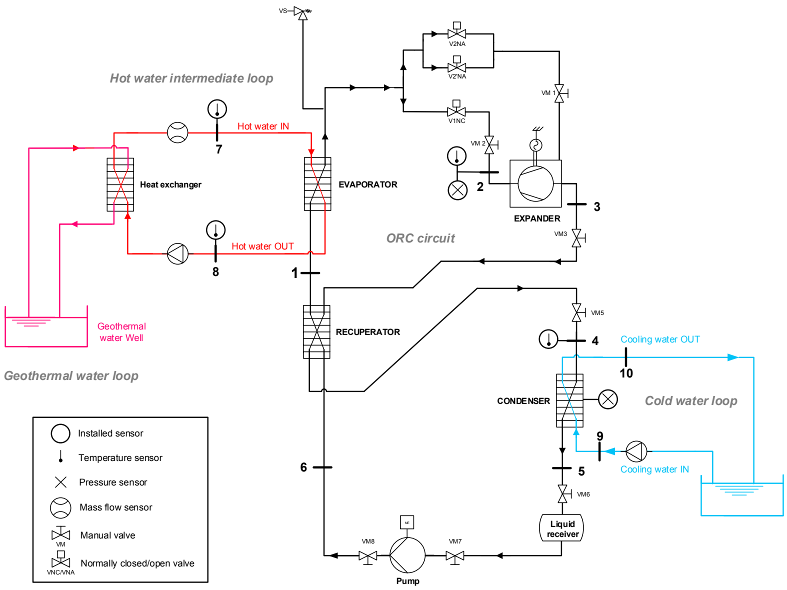

Figure 2. Micro-ORC system schematic layout

2.2. Automatic control logic

The automatic control system, acting on the pump motor inverter, adjusts the pump rotational speed and thus the flow rate of the organic fluid, as the pump is of positive displacement type. In Figure 3 a schematic flow chart of the automatic control logic implemented in the control unit is reported. It is based on the achievement of a target value of superheating degree at the evaporator outlet. Thanks to the acquisition in real-time of the measurements of superheating temperature (T_2 in Fig.2) and evaporation pressure, the control system calculates the corresponding saturation temperature (T_{ev}) and the superheating degree (SH_m). The SH_m measured value is compared to the target (SH_{tar}), then the inverter increases or reduces the pump speed to reduce the difference between the set point and the measured superheating to zero. For example, if the measured value of superheating degree is higher than the target, the pump speed rises, increasing the working fluid mass flow rate and the evaporation pressure, therefore reducing the superheating degree at constant superheating temperature T_2. Equally, if $SH_m < SH_{tar}$, the inverter slows down the pump to reduce the mass flow rate and consequently the evaporation pressure.

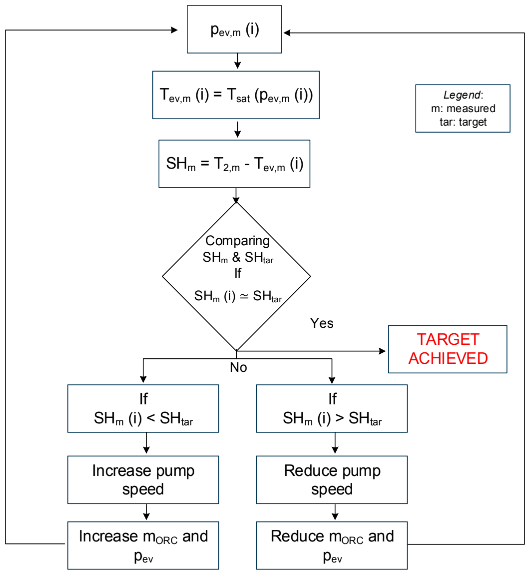

Figure 3. Flow chart of the automatic control logic

2.3. On-board acquisition system

The ORC system under investigation is an industrial realization, provided only with sensors used for the control operation and for the overall monitoring. This instrumentation includes a series of pressure sensors and thermocouples along the ORC and the water external circuit. Pump and expander rotational speed are measured through rotary encoders, while the electric power produced by the expander and absorbed by the pump are acquired by means of voltage and current transducers embedded in the control system. The external circuits of hot and cold water have been provided with thermocouples and volumetric flow meters. Pressure losses along the organic fluid circuit and through the heat exchangers are neglected in this analysis. Since no flow meter is implemented in the ORC circuit, the mass flow rate of the working fluid has been estimated using the pump displacement and rotating speed, as specified in the next section.

Table 2. Installed sensors specifics

Measured variable	Layout points (Fig. 2)	Sensor	Accuracy
ORC temperature	2, 4	Standard Pt100 class B	± 0.3 °C
ORC pressure	2, 4	Gauge manometer	± 1.6 %
Hot water temperature	7, 8	Certified Pt100 class 1/10 DIN	± 0.08 °C
Hot water flow rate	7	Ultrasonic flow meter	± 1 %
Cold water temperature	9	K-type thermocouple	± 1.5 °C
Pump and expander electric power	-	Voltage and current transducers	± 2 %

All the sensors are connected to the control system and the acquired values are displayed on the user interface, and contextually stored in the system memory and available in real-time on the internet [13].
The thermodynamic library CoolProp is adopted in post-processing for the calculation of the physical properties of the working fluid from the measurements of pressure and temperature as inputs. See Table 2 for more information

about the acquisition system specifics.

3. Operation and performance analysis

The data considered in this study have been collected over a long period (almost two years) of quasi stable heat source conditions. In this analysis, a representative operating point of the average working conditions of the system is presented. Hence, the system as well is controlled to work continuously at fixed operating point. This circumstance should partially compensate the uncertainty on measurements and on performance evaluation due to the lack of instrumentation implemented.

A geothermal water temperature constant value was observed during the operations, while only the corresponding flow rate presents very small variations. On the intermediate hot source circuit, the water flow rate is kept at 6.0 l/s by the centrifugal pump, supplying the evaporator with an inlet temperature of 54.2 °C. A cold water flow rate of 7.0 l/s is fed to the condenser with an inlet temperature around 16 °C. On ORC side, the expander inlet temperature (i.e. the maximum temperature of the cycle) is of 51.8 °C. The evaporation pressure, acquired at the expander inlet, is 12.7 bar, corresponding to an evaporation temperature of 48.5 °C. This value, for a given superheating temperature T_2, is implicitly set by the control system, since it regulates the pump speed to achieve the pressure value that gives the superheating degree target. The latter was set to 3.5 °C, considered an optimum value on the basis of previous experimental analysis conducted on the prototype system. These conditions lead to a regulation of the pump rotating speed around 65 rpm. For the pump absorbed electric power, a stable value of 0.45 kW is observed. The expander output is 2.8 kW at a rotational speed around 700 rpm, set by the inverter. See Table 3 for more details on operating variables. The estimation of the mass flow rate of the organic fluid, required for the evaluation of the efficiency of the overall system and of its components, can be obtained through the computation of the volumetric flow rate sucked by the pump, using the pump displacement and its rotational speed, according to Eq. 1.

$$\dot{m}_{ORC} = V_{pp} \cdot N_{pp} \cdot \rho_5 \cdot \eta_{vol} \qquad (1)$$

where V_{pp}, N_{pp}, are, respectively, the displacement and the rotating speed of the pump, ρ_5 is the density value calculated at the pump suction, while η_{vol} is its volumetric efficiency, namely the ratio of the actual flow rate processed by the pump and the theoretical value. The latter has been assumed equal to 92 %, according to previous experiments conducted by the manufacturer. Under these assumptions, the mass flow rate results 0.32 kg/s for the considered working condition. Once the $\dot{m}_{ORC}$ value is determined, the proposed performance indexes can be evaluated for the expander, for the pump and for the overall cycle. For the expander, the global efficiency (η_{exp}) and the filling factor (*FF*) are evaluated through Eq. 4 and Eq. 5.

$$\eta_{exp} = \frac{\dot{W}_{exp,el}}{\dot{m}_{ORC} \cdot (h_2 - h_{3,is})} \qquad (4) \qquad\qquad FF = \frac{\dot{m}_{ORC}}{\rho_2 \cdot N_{exp} \cdot V_{exp}} \qquad (5)$$

While for the pump, the global efficiency (η_{pp}) has the following expression:

$$\eta_{pp} = \frac{\dot{W}_{pp,hy}}{\dot{W}_{pp,el}} = \frac{\dot{m}_{ORC} \cdot (p_{ev} - p_{cond})}{\rho_5 \cdot \dot{W}_{pp,el}} \qquad (6)$$

Finally, the overall cycle performances are computed with the net cycle efficiency (η_{ORC}, Eq. 7) and the back work ratio (BWR, Eq. 8), defined as the pump consumed power ($\dot{W}_{pp,el}$) divided by the expander power output ($\dot{W}_{exp,el}$), which expresses the impact of the auxiliary system on the cycle performance.

$$\eta_{ORC} = \frac{\dot{W}_{exp,el} - \dot{W}_{pp,el}}{\dot{Q}_{ev}} \qquad (7) \qquad\qquad BWR = \frac{\dot{W}_{pp,el}}{\dot{W}_{exp,el}} \qquad (8)$$

It must be pointed out that the quantity $\dot{Q}_{ev}$ in the denominator refers to the thermal power evaluated at water side, since no temperature is acquired at the evaporator inlet on ORC side.

Table 4 collects the performance results obtained thanks to the mass flow rate estimation described above. An expander efficiency close to 53 % was observed, with a filling factor of 0.78. The consumption of the pump is 0.45 kW_{el}, with a pump global efficiency close to 41 %. This value is close to the average efficiency of about 50 % estimated by Landelle et al. in their review on small scale ORC pump performance [14]. A back work ratio (BWR) around 16 % was observed, in line with the ranges expected for R134a as working fluid in subcritical cycle [4]. Finally, the cycle efficiency achieves the 4.4 %, net of the auxiliary electric consumption.

Table 3. Averaged data measured on regular operating conditions

Physical quantity	Symbol	Value
Hot water inlet temperature [°C]	T_7	54.2
Hot water outlet temperature [°C]	T_8	52.2
Cold water inlet temperature [°C]	T_9	16.0
Expander inlet temperature [°C]	T_2	51.8
Evaporation pressure [bar]	p_{ev}	12.7
Condensation pressure [bar]	p_{cond}	5.7
Superheating degree target [°C]	SH_{tar}	3.5
Superheating degree measurement [°C]	SH_m	3.5
Pump rotational speed [rpm]	N_{pp}	64
Expander rotational speed [rpm]	N_{exp}	700

Table 4. Performance calculated at the regular operating point

Performance index	Symbol	Value
Expander efficiency [%]	η_{exp}	52.7
Expander filling factor [-]	FF	0.78
Pump efficiency [%]	η_{pp}	40.7
ORC net efficiency [%]	η_{ORC}	4.4
Back work ratio [%]	BWR	16.1

In Figure 4 the thermodynamic cycle is reconstructed from the experimental data in temperature-entropy diagram. The expander outlet thermodynamic state (whose temperature is not measured) was determined using the CoolProp library from the expander global efficiency, assuming a thermal to electric conversion efficiency equal to 0.8. Figure 5 reports the energy fluxes in a Sankey diagram: from the ideal power available at the expander, major losses are represented by the irreversibilities and by the electro-mechanical conversion losses. The latter contribution, with respect to the isentropic to adiabatic energy losses, could have been underestimated since the generator is rather oversized (11 kW of nominal power).

Considering the very small difference between evaporation and condensation temperature levels, this system appears to be very competitive compared to state-of-the-art micro-scale ORC systems. As future step, it could be interesting to test the ORC system under higher temperatures of hot source, in order to achieve better performance working with larger pressure ratios. For this purpose, the power facility will be used in a test bench installed in Arbizzano (VR), with a 700 kW oil boiler as heat source and a 650 kW compression chiller as cold sink, to investigate the whole range of operating conditions. The acquisition system will be upgraded too, with the addition of temperature sensors at the inlet and outlet of each ORC component, pressure sensors along the circuit and a mass flow meter, to achieve a full characterization of the system and of its components.

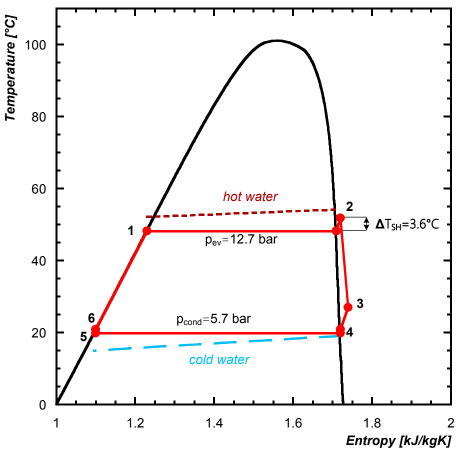

Figure 4. T-s diagram for the ORC regular operating condition

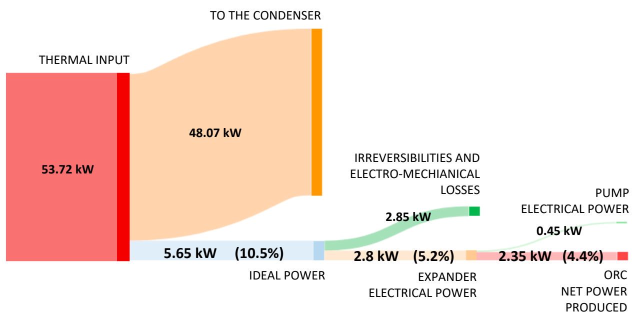

Figure 5. Sankey diagram for the ORC regular operating condition

4. Conclusion

In this paper, an innovative micro-Organic Rankine Cycle for low temperature heat recovery was presented. The system was developed by the company StarEngine S.r.l. and it is installed and currently operating in a pool centre in Goito. The facility operation has been monitoring for a continuous period of two years, demonstrating robustness and good performance. The power plant is composed by three brazed-plate heat exchangers as evaporator, condenser and recuperator of the Rankine cycle, a liquid receiver, an external gear pump and a radial piston expander. Both pump and expander have been designed and manufactured by StarEngine, while other components are commercial product chosen and assembled to create a plug-and-play power facility. The system is provided with a control panel customised by Siemens for this application, which acquires the main experimental data for the monitoring and the controlling of the operation. The installed sensors include two manometers for measuring pressure in evaporation and condensation lines of the ORC circuit. The control logic is based on reducing to zero the difference between the set point of the superheating degree and its measured value, adjusting the pump rotational speed thanks to a frequency inverter. The thermodynamic cycle and the performance were evaluated at the regular operating condition, which is supplied with a constant hot water flow rate at a temperature close to 55 °C, inducing an ORC superheating temperature of almost 52 °C. The cold sink temperature is rather constant around 16 °C, determining an ORC condensation temperature close to 20 °C. Being all the boundary conditions quite constant, the system is set for working at fixed pump rotational speed, for keeping the value of superheating degree equal the set point imposed in the control system. The gross power output was about 2.8 kW for an expander rotational speed of 700 rpm. The pump measured consumption resulted close to 450 W, which corresponds to about the 16 % of the gross produced power. The expander performances were quantified through the filling factor and the global efficiency, which resulted 0.58 and 49.5 %, respectively. A pump global efficiency equal to 43.3 % was obtained, with a volumetric efficiency close to 91 %. The cycle efficiency value was 4.4 %, which is congruent with the state-of-the-art micro-scale ORC systems.

References

[1] Bertani Ruggero. “Geothermal power generation in the world 2010–2014 update report”. *Geothermics* 60 (2016) 31–43. doi.10.1016/j.geothermics.2015.11.003.

[2] Barbier Enrico. “Geothermal energy technology and current status: an overview”. *Renewable and Sustainable Energy Reviews* 6 (2002) 3–65.

[3] Bianchi Michele, De Pascale Andrea. “Bottoming cycles for electric energy generation: Parametric investigation of available and innovative solutions for the exploitation of low and medium temperature heat sources”. *Applied Energy* 88 (2011) 1500–1509. doi: 10.1016/j.apenergy.2010.11.013.

[4] Quoilin Sylvain, Van Den Broek Martijn, Declaye Sèbastien, Dewallef Pierre, Lemort Vincent. Techno-economic survey of Organic Rankine Cycle (ORC) systems. *Renewable and Sustainable Energy Reviews*, 22 (2013) 168–186. doi: 10.1016/j.rser.2013.01.028.

[5] Macchi Ennio, Astolfi Marco. “Organic Rankine Cycle (ORC) Power Systems- technologies and applications”. Woodhead Publishing series in energy, 107, Elsevier, 2017, ISBN: 978-0-08-100510-1.

[6] http://www.enogia.com/docs/datasheets/datasheet-ENO10LT.pdf.

[7] https://electratherm.com/products/power-plus-generator-4200-up-to-35kwe/.

[8] http://www.zuccatoenergia.it/en/products/ulh-series.

[9] http://www.infinityturbine.com/rot06.html.

[10] https://www.orcan-energy.com/en.

[11] Bianchi Michele, Branchini Lisa, De Pascale Andrea, Orlandini Valentina, Ottaviano Saverio, Pinelli Michele, Spina Pier Ruggero Suman Alessio. “Experimental Performance of a Micro-ORC Energy System for Low Grade Heat Recovery”. *Energy Procedia* 129 (2017) 899-906. doi: 10.1016/j.egypro.2017.09.096.

[12] Bianchi Michele, Branchini Lisa, De Pascale Andrea, Melino Francesco, Orlandini Valentina, Ottaviano Saverio, Peretto Antonio, Pinelli Michele, Spina Pier Ruggero, Suman Alessio. “Experimental Investigation with Steady-State Detection in a Micro-ORC Test Bench”. E*nergy Procedia* 126 (2017) 469-476. doi: 10.1016/j.egypro.2017.08.222.

[13] starengine.it

[14] Landelle Arnaud, Tauveron Nicolas, Revellin Rémi, Haberschill Philippe, Colasson Stephane, Roussel Vincent. “Performance investigation of reciprocating pump running with organic fluid for organic Rankine cycle”. *Applied Thermal Engineering* 113 (2017) 962–969. doi: 10.1016/j.applthermaleng.2016.11.096.