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Experimental Performance of a Micro-ORC Energy System for Low Grade Heat Recovery

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Abstract

The state-of-the art of ORC energy systems is mainly dominated by large scale units in the MW range of power output, in the field of heat recovery at mid-high temperature levels (around 200-500°C), where multiple commercial realizations are available. Nevertheless, the cutting-edge niche of micro-ORC energy systems offers good solutions for low-temperature heat recovery. Many prototypes are currently under investigations, but a leading technology is not yet established. This work reports an experimental activity carried out for performance characterization of a prototypal micro-ORC energy system. In particular, the paper presents the test bench developed in the laboratories of the University of Bologna and the first obtained results in terms of thermodynamic performance and main components characteristics. The ORC system comprises a small reciprocating three-piston expander, run on R134a as operating fluid. Heat is provided to the ORC from an external source, via hot water at temperature below 100 °C, in order to simulate a low-enthalpy heat recovery process. The system rejects unused heat via a water cooled condenser. Thus, the investigated ORC is a plug and play system, requiring only to be connected to the hot and cold heat sources. The ORC system has been tested for prolonged operation at various thermal input conditions. In particular, the behavior of the key cycle parameters and performance indexes (e.g. max. and min. pressures, superheating temperature, expander isentropic efficiency, electric power output, etc.) are investigated as function of pump rotational speed (i.e. organic fluid mass flow rate), for three different set point values of the hot source (65 °C, 75 °C, 85 °C). The operating thermodynamic cycle has been completely characterized by means of a real-time measurement and acquisition tool, developed in LabVIEW environment. Performance variations of the system have been monitored: the electric power output ranges between 0.30 to 1.2 kW, with gross efficiency in the range 2.9-4.4 %, while the expander “electro-isentropic” efficiency results in the range of 35-42 %.

Keywords: micro-ORC, experimental test bench, small size energy system, data acquisition, low grade heat recovery.

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1. Introduction

The exploitation of low grade residual heat power fluxes is one of the short-term feasible strategies in order to pursue the primary energy saving target worldwide. This concept, adaptable to a number of different applications, is aimed at exploiting low-value thermal sources that would be wasted otherwise, in order to produce additional electrical power for on-site utilization. Indeed, about 50 % of the world energy consumption is wasted as heat, due to the limitations in the energy conversion processes [1]. The Organic Rankine Cycle (ORC) technology is a proved solution to convert heat into mechanical or electric energy. It has been proposed and applied to recover low/medium enthalpy heat flows (such as industrial wasted heat, internal combustion engines and gas turbines) and renewable thermal sources (biomass, solar, geothermal or ocean energy) [2, 3]. Compared to other more widespread and consolidated power generation technologies [4], the ORC system features several advantages (as detailed in [5]). It must be pointed out that ORC conversion efficiency shows a significant variation with the system size: while large size cutting-edge plants can feature electric efficiency up to 25 %, small and micro scale ORC applications hardly exceed 10 % [5].

In the micro-scale ORC applications, size ranges between 1 kW to few tens of kW and the commonly available hot sources are the combustion products of fossil and/or bio-fuels and solar energy. Despite its versatility, the diffusion of micro-ORC technologies in the market is quite limited, mostly present as prototype solutions [5-6]. Thus, the micro-scale market niche is currently a field where innovation and advanced technologies can still find space.

Several thermodynamic studies can be found in literature regarding micro/small ORC systems, mainly involving the ORC expander characterization [7-9], the choice of the most promising organic fluid for low temperature exploitation [10-12] and the feasibility of the ORC technology in different applications [13]. Examples of experimental studies on micro ORC prototypes can be found in [11, 14-18].

In particular, the available literature on expanders for ORC shows many examples of scroll expanders operated with R134a as fluid [7]. Another volumetric expander type applied for ORC is the Piston solution; they can be divided into several groups, as reciprocating, rotary, gerotor, rolling and swing piston expanders [19]; in the literature they are frequently tested with CO_2 as working fluid in trans-critical cycle [7]. However, the using of traditional reciprocating piston expander in ORC systems is not yet become a common practice [19].

The innovative contribution of this study is aimed at characterizing a prototypal micro-ORC in the kW power size range, based on a piston reciprocating expander, using R134a as working fluid and exploiting hot water with temperature below 100°C; a preliminary experimental campaign under various operating conditions has been performed.

Nomenclature		**Greek letters**	
AI	Analog input	η	Efficiency
FPGA	Field Programmable Gate Array	ρ	Density
FPR	Fluid Power Ratio	**Subscripts**	
FS	Full Scale		
h	Enthalpy	*COLD*	Cold water supply
I/O	Input/Output	*el*	Electric
$\dot{m}$	Mass flow rate	*exp*	Expander
n	Rotational speed	*gross*	Gross
ORC	Organic Rankine Cycle	HOT	Hot water supply
p	Pressure	*in*	Input (referred to thermal power introduced)
P	Power	*iso*	Isentropic
PCB	Printed Circuit Board	*l*	Liquid phase
$\dot{Q}$	Thermal power	*net*	Net
R	Reading value	*out*	Output (referred to thermal power discharged)
SH	Superheating degree	*pump*	Pump
T	Temperature	*Rec*	Recuperator
$\dot{V}$	Volumetric flow rate	*SAT*	Saturation
VBA	*Visual Basic for Application*	*v*	Vapor phase

2. Test bench description

Figure 1 shows the micro-ORC prototype under investigation and a three-dimensional sketch, while in Figure 2 the detailed layout is reported, including the external circuits for hot and cold water supply, designed and set up in the laboratory, in order to test the micro-ORC. This ORC system is designed in order to limit the footprint area that is equal to 80x85cm. The system is rated for an input thermal power around 30 kW. It consists of an evaporator, a positive displacement expander, a gear pump, a shell and tube condenser and a recuperator heat exchanger, to recover residual heat from vapor after the expansion. The expansion machine is a prototype designed and developed by StarEngine Company: it is a reciprocating piston model, made of three radial pistons, placed at 120° and moving the same crankshaft, for a total displacement equal to 293 cm^3 (more information on patent document [20]). The expander admission and discharge valves are mechanically driven by the crankshaft rotation. The expander is directly coupled to a permanent magnet electric generator in a hermetical sealed case. Since no transmission is interposed, expander and generator work at the same rotational speed, which can vary in the range from 400 rpm to 1800 rpm. The external surface of the machine has been thermally insulated by means of mineral wool panels, in order to reduce heat transfer losses, which have been demonstrated not negligible in analogues applications [21]. The ORC circulation pump is a prototypal volumetric external gear pump, driven by a three-phase motor that can work at a rotational speed between 250 rpm and 900 rpm by means of an inverter. The system is also provided with a by-pass line at the outlet of the evaporator, which allows the working fluid to flow through the external casing of the expander, by-passing the cylinders; this expedient is used during start-up operation, in order to warm up the expander body and avoid possible thermal stresses due to a cold start-up.

The working fluid is R134a, which has a critical temperature of 101 °C and a critical pressure equal to 40 bar. Lubricant oil for moving parts of both expander and pump is mixed with the working fluid, as the system is not provided with an external oil circuit. The electric load is simulated by a resistive load, for a maximum electric output power equal to 3 kW. The power plant is provided with a safety valve with a set pressure value equal to 25 bar.

Thermal input is provided by a 500 litres electric water heater (named puffer in Fig. 2), with a total absorbed electric power nearly equal to 32 kW. The pump P2 circulates a water flow rate ranging between 1 l/s and 2.6 l/s. A thermal power between 8 kW and 30 kW can be continuously simulated for the test bench, regulating flow rate and heaters.

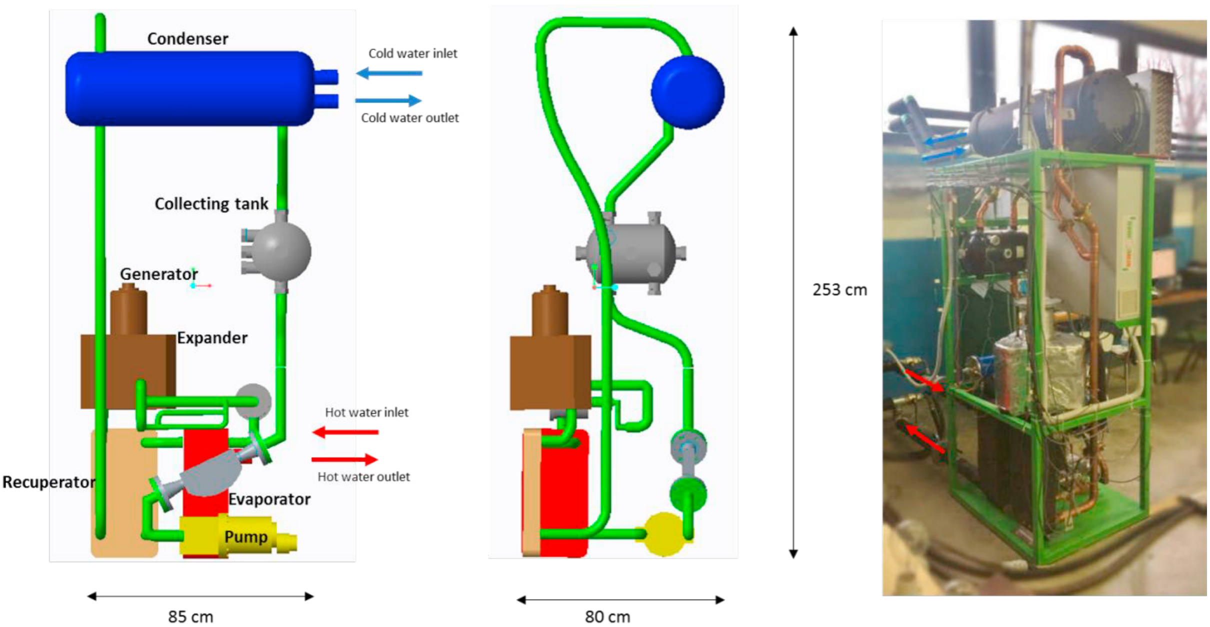

Figure 1 - ORC prototype: a) front view, b) side view, c) photo.

Cold water is extracted from a well by pump P4 and stored in a 300 litres tank, from which is circulated through the condenser circuit by pump P3. Condensation water temperature, as it has been empirically observed, varies between 16 °C in winter and 22 °C in summer. Cold water flow rate can be regulated with P3 pump between 1 l/s and 2.8 l/s. More information on the test bench set up are available in [22].

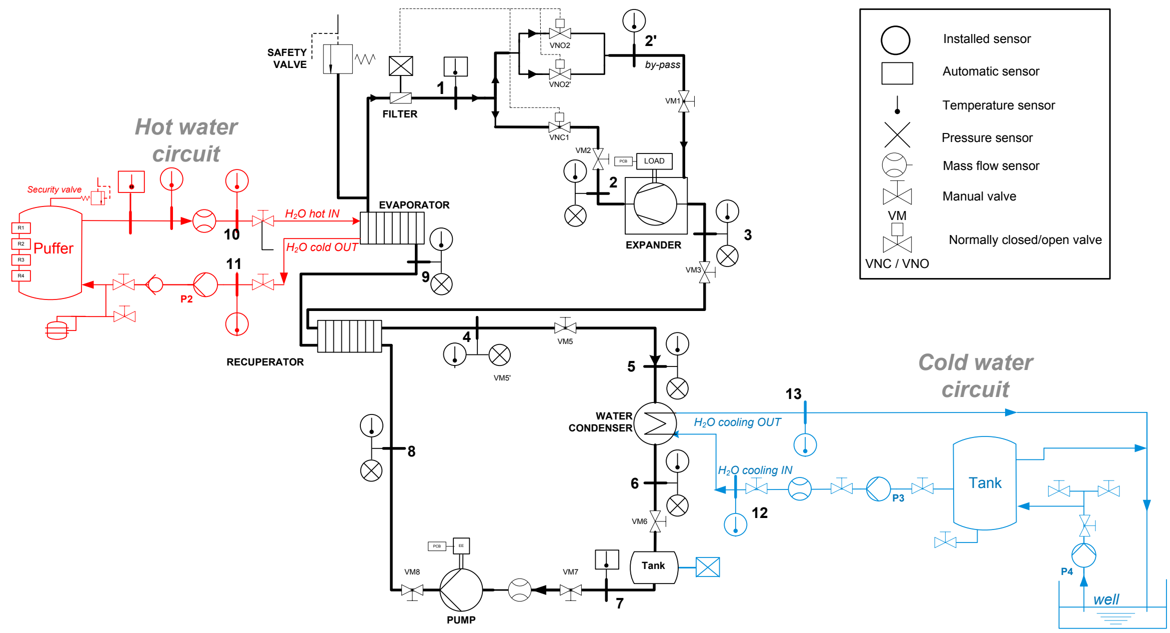

Figure 2 - Test bench layout.

2.1. Test bench instrumentation

The on-board governor of the present ORC system, that consists in an industrial-standard PLC, has been coupled with a stand-alone measurement system able to detect temperature, pressure and mass flow rate values of the ORC system and hot/cold water supply lines. The instrumentation for measurements, signal conversion and analysis of the ORC system includes a number of sensors, a reconfigurable I/O device and an acquisition software, ad-hoc developed in LabVIEW platform. Table 1 lists the main specifications about the sensors apparatus.

Table 1 - Acquisition system specifications

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 % R *	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 % R *	NI9207-Current AI
Cold water flow rate	12	Magnetic flow meter	0-9.8 l/s*	4-20 mA	0.5 % R *	
Electrical output power	-	PCB mounted voltage trasducer coupled with Rogowski coil current sensor	0-400 V 0-5 A	0-4 V	0.1 % R 0.2 % R	

* Provided by manufacturer

Sensors have been located at inlet and outlet branches of each ORC components, allowing a complete characterization of the system. Organic fluid temperature values are measured by T-type thermocouples and, in the same inspection connections, pressure values are acquired by means of ceramic absolute pressure transducers. A Coriolis-model device is used to measure the organic fluid mass flow rate and density. Temperature values on the hot and cold water circuits are measured by K-type thermocouples, while two magnetic flow meters have been installed for volumetric flow rates acquisition. A printed circuit board (PCB) has been realized at the laboratory to acquire electrical output power, while the mechanical output power is not directly measured in the current test bench arrangement. All temperature and pressure sensors have been calibrated at the laboratory in their operative ranges (see values in Table 1).

2.1.1. Acquisition system

The hardware used for data acquisition is a National Instrument CompactRIO, which includes a FPGA chassis and a Real-Time embedded controller. This device has been provided with a series of FPGA modules for analogue input, based on the type of signals that have to be acquired and processed (Table 1).

The acquisition software is integrated with the thermodynamic library CoolProp [23]. In order to evaluate the power exchanged at each component, the fluid property values are calculated by means of the CoolProp library using temperature and pressure as input values. Tillner-Roth et al. [24] estimated the error values for properties calculation using the equation of state implemented in CoolProp. All mentioned operations are realized in real time, with a time step equal to 1 second. Besides, the real-time thermodynamic cycle is plotted on temperature-entropy and pressure-enthalpy diagrams, during the experimental tests.

Performance indexes have been estimated, starting from measured data, by means of the expressions listed below (with reference to Figure 2). The exchanged thermal power (eq.s 1-4) are evaluated in terms of inlet/outlet enthalpy variation through the considered heat exchanger (respectively, evaporator, condenser, recuperator vapor and liquid side).

The expander thermodynamic power (P_{exp}), evaluated in terms of enthalpy variation through the expander, is calculated according to eq. 5. The pump consumption (P_{pump}) is calculated in the hydraulic form (eq. 6).

The cycle efficiency (respectively $\eta_{ORC,gross}$ and $\eta_{ORC,net}$) and the isentropic efficiency ($\eta_{iso,el}$) values are referred to the electrical power (P_{el}). The Fluid Power Ratio (FPR) index (eq. 10) has been also introduced as the ratio between the electrical power measured and the expander thermodynamic power (P_{exp}). This parameter takes into account all the losses occurring in the energy transfer from the fluid to the electric output.

$$\dot{Q}_{in} = \dot{m}_{ORC}(h_2 - h_9) \quad (1)$$

$$\dot{Q}_{out} = \dot{m}_{ORC}(h_5 - h_6) \quad (2)$$

$$\dot{Q}_{Rec,v} = \dot{m}_{ORC}(h_3 - h_4) \quad (3)$$

$$\dot{Q}_{Rec,l} = \dot{m}_{ORC}(h_9 - h_8) \quad (4)$$

$$P_{exp} = \dot{m}_{ORC}(h_2 - h_3) \quad (5)$$

$$P_{Pump} = \frac{\dot{m}_{ORC} \cdot (p_8 - p_6)}{\rho_7} \quad (6)$$

$$\eta_{ORC,gross} = \frac{P_{el}}{Q_{in}} \quad (7)$$

$$\eta_{ORC,net} = \frac{P_{el} - P_{Pump}}{Q_{in}} \quad (8)$$

$$\eta_{iso,el} = \frac{P_{el}}{\dot{m}_{ORC} \cdot (h_2 - h_{3,iso})} \quad (9)$$

$$FPR = \frac{P_{el}}{P_{exp}} \quad (10)$$

3. Results

The preliminary test campaign has been conducted for different set points of the hot water temperature (T_{HOT}) and varying the ORC pump rotational speed (n_{pump}), thus regulating the organic fluid mass flow rate ($\dot{m}_{ORC}$) and the evaporation pressure (p_2). Hot and cold water flow rates have been kept constant and equal to the maximum values achievable with the two pumps P2 and P3.

In order to acquire the ORC performance, a steady-state condition has been identified for each T_{HOT} set point and pump rotational speed value. The results are presented in terms of averaged values calculated for every identified steady-state interval. Various methods for steady state detection have been subject of some experimental studies [25-26]. In this analysis, the approach is to identify a steady-state interval as a period of a duration greater than or equal to 300 s, in which a variation of measured quantities less than 2 % (referring to the average value) is observed. An in house-developed VBA calculation code has been realized for the off-line analysis of the acquired data.

Table 2 presents some significant data obtained from the preliminary test campaign.

Table 2 – Main experimental measured data for three different hot water temperature set points

Set points		*Averaged measured quantities or ranges*							
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)	$\dot{Q}_{in}$ [kW] (min-max)	$\dot{Q}_{out}$ [kW] (min-max)	p_3 [bar] (min-max)
65	270-450	2.63	17.5	2.80	0.052-0.103	10.9-14.4	10.4-20.3	9.60-19.6	5.78-6.13
75	375-600	2.63	18.0	2.80	0.083-0.136	13.0-16.9	16.1-25.8	15.3-25.0	6.00-6.39
85	270-600	2.63	17.3	2.80	0.055-0.132	11.0-16.8	11.7-25.4	10.2-24.6	5.67-6.30

The cold water conditions are quite constant in the performed test and consequently the obtained condensation pressure value is almost the same (close to 6 bar) for all the considered operating points.

Figures 3 a) and b) show the expansion ratio (p_2/p_3) and the superheating degree (T_2-$T_{SAT}(p_2)$) values as functions of the organic fluid mass flow rate, for all the investigated set points. The evaporating pressure value varies between 11 bar and 17 bar, with a pressure ratio ranging from 1.8 to 2.7 with a rising trend versus $\dot{m}_{ORC}$. As expected, for a fixed T_{HOT}, the increase of the pump rotational speed increases the evaporating pressure and reduces the superheating degree. Indeed, the maximum ORC temperature (T_2) keeps close to the hot water temperature (T_{HOT}), for each investigated set-point, thus superheating degree value strictly depends on T_{SAT} (p_2).

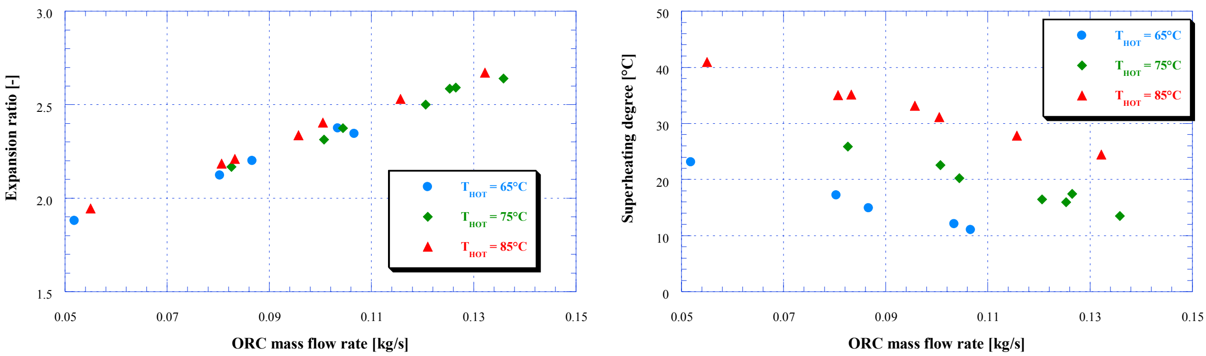

Figure 3 – Expansion ratio (a) and superheating degree (b) versus ORC mass flow rate.

Figure 4 presents the trend of the produced electric power (a) and the ORC efficiency (b) as functions of the superheating degree. The electric power increases with T_{HOT} and decreases with the superheating. Power output values range between 300 W and 1100 W. Also, the ORC efficiency shows similar trends versus T_{HOT} and versus the superheating degree. The efficiency values, for the tested operating points, range from 2.9 % to 4.4 %, increasing with the superheating degree decrease (i.e., with the $\dot{m}_{ORC}$ increase). In particular, both gross and net efficiency values are shown in Fig. 4 (b). The effect of the pump consumption (P_{pump}) is more significant (in terms of efficiency) at high power and high pressure ratio values.

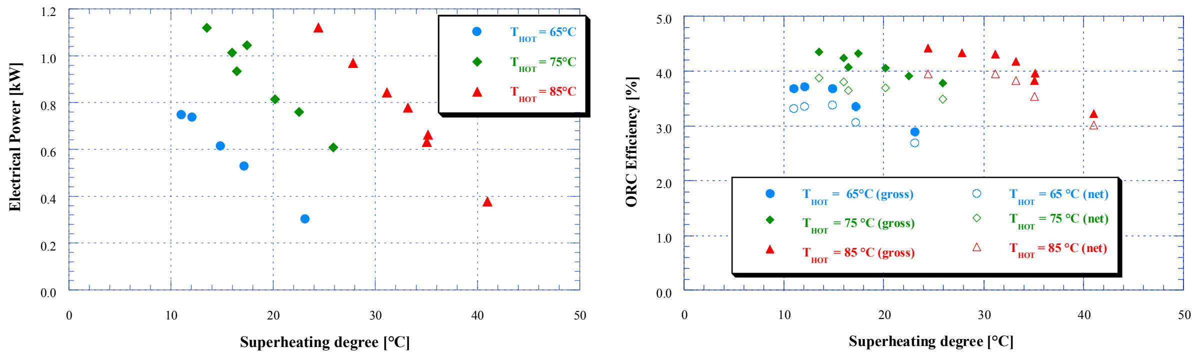

Figure 4 – Electric output power (a) and ORC efficiency (b) versus superheating degree.

Figure 5 shows the expander isentropic efficiency (a) and the FPR values (b) plotted versus the expansion ratio. The isentropic efficiency trend shows a modest change with the expansion ratio, as it varies between 35 % and 42 %, while no relevant effect of T_{HOT} is observed on $\eta_{iso,el}$. The FPR clearly increases with the expansion ratio increased, up to a value close to 96 % for high input load.

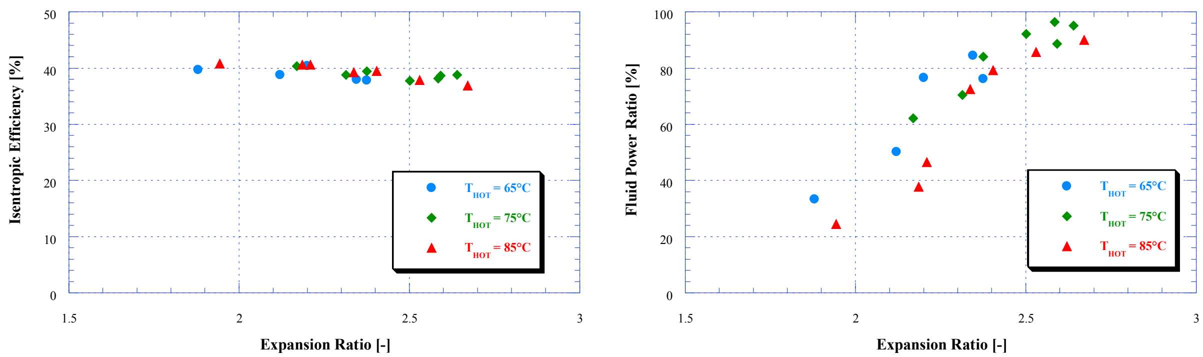

Figure 5 - Isentropic efficiency (a) and fluid power ratio (b) versus expansion ratio.

4. Conclusions

In this paper, an experimental micro-ORC setup for low-temperature applications was presented. A test bench was implemented in order to obtain experimental data for the characterization of the energy system. A number of sensors of temperature, pressure and flow rate have been installed in both organic fluid and water circuits. All measured data, along with the CoolProp thermodynamic library application, allowed to obtain the exchanged thermal power flows, in terms of enthalpy variation between the inlet and outlet of the heat exchangers (evaporator, recuperator and condenser) of the ORC system. The performed experimental test campaign shows that the system is able to operate with hot source temperature values ranging from 65 °C to 85 °C, producing electric power output values between 300 W and 1.2 kW.

An additional test campaign is in progress, with the purpose to extend the range of operating conditions and fully characterize the system behavior. For example, a further investigation on the influence of the auxiliary consumption on the overall efficiency will be performed, as well as a detailed evaluation of thermal losses through the expander walls.

Acknowledgments

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References

[1] Siemens power generation division,"Waste heat recovery with organic Rankine cycle technology" (2014), available at: http://www.energy.siemens.com/mx/pool/hq/power-generation/steam-turbines/downloads/brochure-orc-organic-Rankine-cycle-technology_EN.pdf.

[2] Feng Y,Hung T, Zhang Y, Li B, Yang J, Shi Y. Performance comparison of low-grade ORCs (organic Rankine cycles) using R245fa, pentane and their mixtures based on the thermoeconomic multi-objective optimization and decision makings. Energy, Volume 93, Part 2, 2015, pp. 2018-2029. doi: 10.1016/j.energy.2015.10.065.

[3] Velez F, Segovia JJ, Martín MC, Antolín G, Chejne F, Quijano A. A technical, economical and market review of organic Rankine cycles for the conversion of low-grade heat for power generation. Renewable and Sustainable Energy Reviews, Volume 16, Issue 6, 2012, pp. 4175-4189. doi: 10.1016/j.rser.2012.03.022.

[4] Bianchi M, Branchini L, De Pascale A, Peretto A. Application of environmental performance assessment of CHP systems with local and global approaches. Applied Energy, Volume 130, 2014, pp. 774-782. doi: 10.1016/j.apenergy.2014.04.017.

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

[6] Thomas Tartière, ORC Market: A World Overview (2016), available at: http://orc-world-map.org/analysis.html (accessed in January 2017).

[7] Imran M, Usman M, Park BS, Lee DH. Volumetric expanders for low grade heat and waste heat recovery applications. Renewable and Sustainable Energy Reviews, Volume 57, 2016, pp. 1090-1109. Doi: 10.1016/j.rser.2015.12.139.

[8] Lemort V, Guillaume L, Legros A, Declaye S, Quoilin S. A comparison of piston, screw and scroll expanders for small scale rankine cycle systems (2013). Proceedings of the 3rd International Conference on Microgeneration and Related Technologies.

[9] Weiß AP. Volumetric expander versus turbine: which is the better choice for small orc plants? 3rd International Seminar on ORC Power Systems, October 12-14, 2015, Brussels, Belgium.

[10] Dong L, Liu H, Riffat S. Development of small-scale and micro-scale biomass-fuelled chp systems: a literature review. Applied Thermal Engineering, Volume 29, Issues 11–12, 2009, pp. 2119-2126. Doi: 10.1016/j.applthermaleng.2008.12.004.

[11] Qiu G, Shao Y, Li J, Liu H, Riffat SB. Experimental investigation of a biomass-fired ORC-based micro-CHP for domestic applications. Fuel, Volume 96, 2012, pp. 374-382. Doi: 10.1016/j.fuel.2012.01.028.

[12] Branchini L, De Pascale, A., Peretto A, Systematic comparison of ORC configurations by means of comprehensive performance indexes, Applied Thermal Engineering, Vol. 61, Issue 2, 2013, pp. 129–140, DOI: 10.1016/j.applthermaleng.2013.07.039.

[13] Tchanche BF, Lambrinos G, Frangoudakis A, Papadakis G. Low-grade heat conversion into power using organic Rankine cycles – A review of various applications. Renewable and Sustainable Energy Reviews, Volume 15,2011, pp. 3963–3979. Doi: 10.1016/j.rser.2011.07.024.

[14] Li M, Wang J, He W, Gao L, Wang B, Maa S, Dai Y. Construction and preliminary test of a low-temperature regenerative Organic Rankine Cycle (ORC) using R123. Renewable Energy, Volume 57, 2013, pp. 216-222. Doi: 10.1016/j.renene.2013.01.042.

[15] Quoilin S, Lemort V, Lebrun J. Experimental study and modeling of an Organic Rankine Cycle using scroll expander. Applied Energy vol. 87, issue 4, 2010, pp. 1260–1268. Doi: 10.1016/j.apenergy.2009.06.026.

[16] Declaye S, Quoilin S, Guillaume L, Lemort V. Experimental study on an open-drive scroll expander integrated into an ORC (Organic Rankine Cycle) system with R245fa as working fluid. Energy vol. 55 issue 4 ,2013, pp. 173-183. Doi: 10.1016/j.energy.2013.04.003.

[17] Borsukiewicz-Gozdur A. Experimental investigation of R227ea applied as working fluid in the ORC power plant with hermetic turbogenerator. Applied Thermal Engineering vol. 56 issue 1-2, 2013, pp. 126-133. Doi: 10.1016/j.applthermaleng.2013.03.039.

[18] Bracco R, Clemente S, Micheli D, Reini M. Experimental tests and modelization of a domestic-scale Organic Rankine Cycle. Energy, Volume 58, 2013, pp 107-116. Doi: 10.1016/j.energy.2012.12.016.

[19] Zywica G, Kaczmarczyk TZ, Ihnatowicz E. A review of expanders for power generation in small-scale organic Rankine cycle systems: Performance and operational aspects. Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy, vol. 230 issue 7, pp. 669-684. Doi: 10.1177/0957650916661465.

[20] Zampieri, Gino. "CLOSED-CYCLE PLANT." U.S. Patent No. 20,160,032,786. 4 Feb. 2016.

[21] Declaye S, Quoilin S, Guillaume L, Lemort V. Experimental study on an open-drive scroll expander integrated into an ORC (Organic Rankine Cycle) system with R245fa as working fluid. Energy, vol. 55, 2013, pp. 173-183.

[22] Ancona, MA, Bianchi M, Branchini L, De Pascale A, Melino, F, Orlandini, V, Ottaviano S, Peretto A, Pinelli M, Spina PR, Suman, A. A Micro-ORC Energy System: Preliminary Performance and Test Bench Development. Energy Procedia, volume 101, (2016), pp. 814-821. Doi: 10.1016/j.egypro.2016.11.103.

[23] Bell IH, Wronski J, Quoilin S, Lemort V. Pure and pseudo-pure fluid thermophysical property evaluation and the open-source thermophysical property library CoolProp. Ind. Eng. Chem. Res; vol. 53 issue 6, 2014, pp.2498–508. Doi: 10.1021/ie4033999.

[24] Tillner-Roth R, Baehr HD, An international standard formulation for the thermodynamic properties of 1, 1, 1, 2-Tetrafluoroethane (HFC-134a) for temperatures from 170 K to 455 K and pressure up to 70 MPa. Journal of Physical and Chemical Reference Data vol. 23, issue 5, pp. 657-729 1994. Doi: 10.1063/1.555958.

[25] Woodland BJ, Braun JE, Groll E, Horton WT. Experimental testing of an Organic Rankine Cycle with scroll-type expander. International Refrigeration and Air Conditioning Conference at Purdue, July 16-19, 2012.

[26] Lecompte S, Oyewunmi OA, Markides CN., van den Broek M, De Paepe M. Preliminary experimental results of an 11 kWe organic Rankine cycle. In 8th International Conference on Applied Energy (2016).