Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 126 (201709) 469–476

Energy Procedia

www.elsevier.com/locate/procedia

72nd Conference of the Italian Thermal Machines Engineering Association, ATI2017, 6-8 September 2017, Lecce, Italy

Experimental Investigation with Steady-State Detection in a Micro-ORC Test Bench

Bianchi M.[a], Branchini L.[a], De Pascale A.[a], Orlandini V.[a], Ottaviano S.[a,b*], Peretto A.[a] , Melino F.[a], Pinelli M.[b], Spina P.R.[b], Suman A.[b]

[a] *Università di Bologna – DIN, Viale del Risorgimento 2, 40136, Bologna, Italy*
[b] *Università di Ferrara- ENDIF, via Saragat 1, 44122, Ferrara, Italy*

Abstract

The exploitation of low grade thermal sources is recognized as a feasible strategy 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 heat fluxes that would be wasted otherwise; additional useful electric power can be produced locally, with ORC energy systems; this is one of the most promising heat recovery solutions.
In particular, the paper refers to the test bench developed in the laboratories of the University of Bologna; a prototypal micro-ORC energy system is here investigated. The micro-ORC system presents a reciprocating three-piston expander operated with refrigerant fluid. Heat is provided to the ORC from via hot water at low temperature, in order to simulate a constant low-enthalpy heat recovery process. The system rejects unused heat via a water-cooled condenser, dependent on the external ambient conditions.
The test bench layout and the real-time data acquisition system, developed in the LabVIEW environment, are here described. In particular, the paper focus is on the system steady-state detection methodology. Starting from an experimental campaign, steady-state operational points are identified through an appropriate literature approach. The measured quantities and calculated performance have been post-processed in order to evaluate the influence on steady state detection, of different hot source temperature set points. Moreover, the selected steady-state detection method is suitable for real-time implementation, due to its simple formulation and the low number of variables required to be stored at time step of acquisition.

Keywords: ORC; test bench; thermodynamic measurements; system efficiency; steady state detection

1. Introduction

The Organic Rankine Cycle (ORC) is an advanced power generation technology commonly used to convert low grade heat into electricity, for a wide range of power values (scales from a fraction of kW_e to several MW_e). ORC technology results now mature and advantageous in many ways and it has shown a renewed interest over the last

* Corresponding author. Tel.: +39 051 20 9 3310; fax: +39 051 20 9 3313.
E-mail address: saverio.ottaviano@unife.it.

1876-6102
10.1016/j.egypro.2017.08.222

decades thanks to its flexibility and easy maintenance. At low temperatures, organic working fluids lead to higher cycle efficiency than water and these kinds of fluids are preferable, leading to high turbine efficiency in both full and partial load conditions. Almost all the units available on the market are in the medium to-high power range, while micro-small size are still in demonstration phase, but their application could save primary energy and reduce pollutant emissions [1]. Small and micro size ORCs are interesting for several applications, such as electric generation in remote area, domestic cogenerative units or trigeneration applications, etc. Recently, there have been many experimental investigations on small scale ORC, focusing on design optimization, fluid selection, expander technologies, operating conditions, components performance or complete cycle, dynamic control and the experimental analysis are useful for model validation and data-feeding [2]. In particular, process data employed for benchmark analysis should be collected when steady-state conditions have been achieved, in order to get realistic and meaningful results from experimental test. Data accuracy is of great importance for power plant on-line performance monitoring and it is fundamental to implement efficient methods for online steady-state detection. Moreover, power plants steady state is not *a priori* defined and a tolerable constancy of the mean values of measurements, over a given period of time, depends on the nature of the system under investigation.

The issue of steady-state detection has been discussed by a number of researchers in the literature. For instance, an available method is proposed by Kim & al. [3]. This technique is based on standard deviation calculated over a time moving window. Steady-state is declared when the moving deviation lies under an established threshold over a predefined time period. This approach requires storing past measurements over the whole moving window, which is critical for real-time applications. Furthermore, using a normal average, instead of a weighted one, creates a delay in the characterization of process measurement. This delay can cause detection problems in periods where the signal varies in a short time period.

Another method, called *R-test*, has been proposed by Cao & Rhinehart [4], based on a ratio of variances evaluation: when this ratio is lower than an arbitrary value, the process reaches the steady-state condition. The method does not need to store past measures and it is computationally inexpensive compared to Kim's method [3].

Nomenclature

Subscripts

Cold	Cold Source
el	Electric
EVAP	Evaporator
EXP	Expander
f	Filtered Value
i	Instant
iso	Isentropic
rrc	Reversible recuperation cycle

Roman symbols

FS	Full Scale
h	Enthalpy [kJ/kg K]
Hot	Hot Source
$\dot{m}$	Mass flow rate [kg/s]
Max	Maximum
min	Minimum
ORC	Organic Rankine Cycle
P	Electric Power [kW]
p	Pressure [bar]
PCB	Printed Circuit Board
Q	Thermal Power [kW]
RV	Reading Value
R	Ratio of Variances [-]
s	Estimated Variance [-]
SP	Set-Point hot source temp. [°C]
T	Temperature [°C]
v	Measured Variance [-]
$\dot{v}$	Volumetric flow rate [l/s]
x	Acquired Value

Greek letters

Δ	Variation
ρ	Density [kg/m^3]
λ	Filter Factor [-]
δ	Mean Squared Difference [-]
η	Efficiency [%]

A third method available in literature has been suggested by Jiang & al. [5]. Using wavelet-based multi-scale data processing, the process trends are first extracted from raw measurements by eliminating random noise and abnormalities. The process status at each time point is then analyzed according to the wavelet transform of the extracted process trends. This method appears to be reliable for detecting rate of change in variables and estimating the measurement status at a point in time; in this case, if measures are affected by nonrandom errors, the detection could be seriously corrupted; experience with the process is essential to determine key parameters and general guidelines for its application need more studies [5].

Therefore, in this paper the second steady-state detection method, named as *R-test*, has been applied to process measurements data of the micro-ORC power generation unit, in order to obtain steady-state intervals and evaluate the system performance.

2. Aim of the study

The general aim of this study is the definition and identification of ORC steady-state operational points. Once steady-state conditions are identified, an evaluation of the system performance at different hot source temperature set points is carried out. The ORC internal layout and the external sources circuits, with information about installed sensors and developed real time acquisition system are described in Section 3. Section 4 presents the steady state identification method and its application for three different test cases, performed at various superheated degrees and at similar working fluid mass flow rate, maximum and minimum ORC pressures. Section 5, finally, presents and discussed the efficiency indexes identified to compare at steady state conditions the ORC performance at different hot source set point temperatures.

3. Experimental test facility

Figure 1 shows the test facility layout, including the micro-ORC and the external circuits for hot and cold water supply, designed and set up in the laboratory. The system is rated for an input thermal power around 30 kW_{th}. The ORC consists of an evaporator, an expander, a gear pump, a shell and tube condenser and a recuperator heat exchanger, for internal heat recovery after the expansion. More information about the system and its components are available in [6], where a preliminary overview has been presented. The expansion machine is a reciprocating radial pistons model, with mechanically driven admission and discharge valves. 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, varying in the range from 400 rpm to 1800 rpm. The external surface of the expander has been thermally insulated by means of mineral wool panels, in order to reduce heat transfer losses.

The ORC circulation pump is a prototypal volumetric external gear pump, driven by a three-phase motor that can work at different rotational speeds (ranging between 250 rpm and 900 rpm) by means of an inverter. The system is 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 thermal stresses due to a cold start-up. Actually, the working fluid is R134a and 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. Thermal input is provided by an electric water heater (puffer in Figure 1) and the pump P2 guarantees the water flow rate circulation (ranging between 1 l/s and 2.6 l/s). The thermal input power can be continuously simulated in the range 8 - 32 kW, by regulating hot water flow rate and heaters. Through pump P4, cold water is extracted from a well and stored in a 300 liters tank. Cold water flow rate at the condenser can be regulated via pump P3.

A stand-alone measurement system has been developed and it is able to detect temperature, pressure and mass flow rate values of the ORC system and of the hot/cold water supply lines. The instrumentation for measurements, signal conversion and analysis of the ORC system includes various sensors, listed in Table 1 and shown in Figure 1. All temperature and pressure sensors have been calibrated at the laboratory in their operative ranges (see values in Table 1). Additional information on the test bench set up are provided in [6].

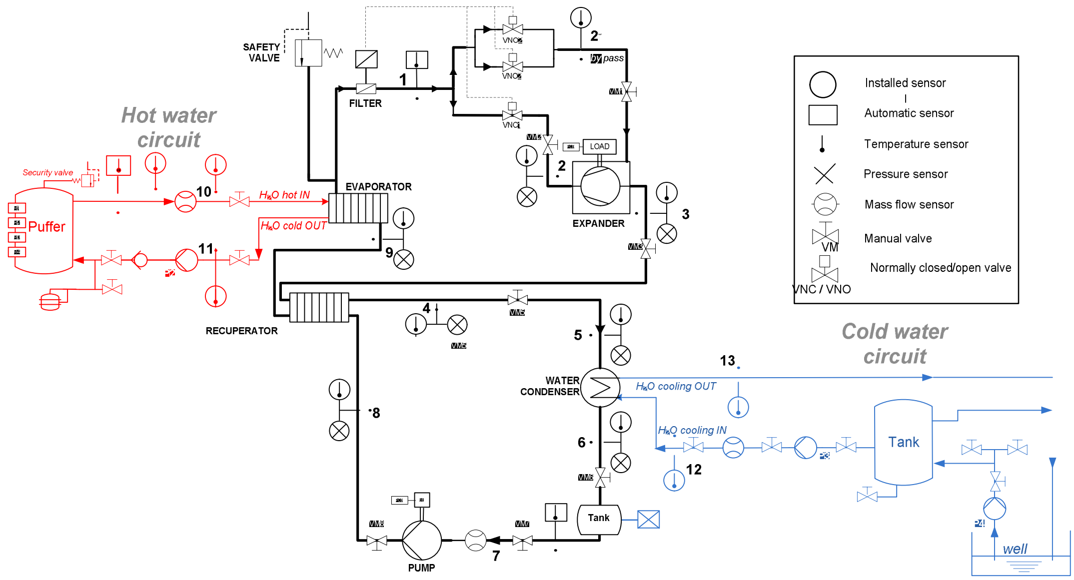


Figure 1 – Test bench layout

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 % 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	

* Provided by sensor manufacturer

Sensors have been located at inlet and outlet branches of each ORC components, allowing a complete thermodynamic characterization of the ORC; mass flow rate and temperature values are measured in the hot and cold water circuits, to evaluate the heat exchanged between the ORC system and the hot and cold sources. A National Instrument CompactRIO platform is used to collect the experimental data measured by all the sensors. A real-time acquisition software has been developed in LabVIEW environment; a front acquisition panel allows the ongoing monitoring of the ORC system operating parameters during the tests. Directly measured data are updated with a time step equal to 1 s, while electric current and voltage signals are acquired with a 10 kHz frequency; thermal power flows are calculated in terms of enthalpy difference between the inlet and outlet of the considered component and directly showed in the front panel. The enthalpy values are calculated as functions of temperature and pressure measured values, using the thermodynamic library CoolProp [7], which has been integrated in the acquisition software. The ORC power, the exchanged heat flows, the cycle and expander efficiency values, pressure drops, and other operating variables are calculated in real-time. Moreover, all the ORC thermodynamic states in the measuring sections are visualized on temperature-entropy and pressure-enthalpy diagrams, thus the thermodynamic cycle can be on-line monitored. All the data acquired and evaluated have been collected and post-processed to identify the steady-state system conditions, as described in the following sections.

4. Steady state identification methodology

The *R-test* approach has been applied as steady-state identification method. As deeply described in [4] and summarized below, this method is a modification of the primitive statistical *F*-test; *R* represents the ratio of two estimated variances, calculated by means of two different approaches on the same set of data, according to eq.(1):

$$R = \frac{s_1^2}{s_2^2} \qquad (1)$$

The first estimated variance term in eq.(1) is evaluated, at each time-step i, as:

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

where $\nu_{f,i}^2$ is an exponentially weighted moving variance (based on the difference between the data and the estimated average), calculated according to eq.(3,4):

$$x_{f,i} = \lambda_1 x_i + (1-\lambda_1)\, x_{f,i-1} \qquad (3); \qquad \nu_{f,i}^2 = \lambda_2 (x_i - x_{f,i-1})^2 + (1-\lambda_2)\, \nu_{f,i-1}^2 \qquad (4)$$

where $x_{f,i}$, is the filtered value of the process measurement at the i-th time step x_i and λ_1 is the filter factor. The filtered value depends on the filtered value at the previous time step $x_{f,i-1}$ and it provides an estimation of the data mean value.

The second estimated variance s_2^2, in eq.(1) is calculated based on the mean squared difference of successive data $\delta_{f,i}^2$, as:

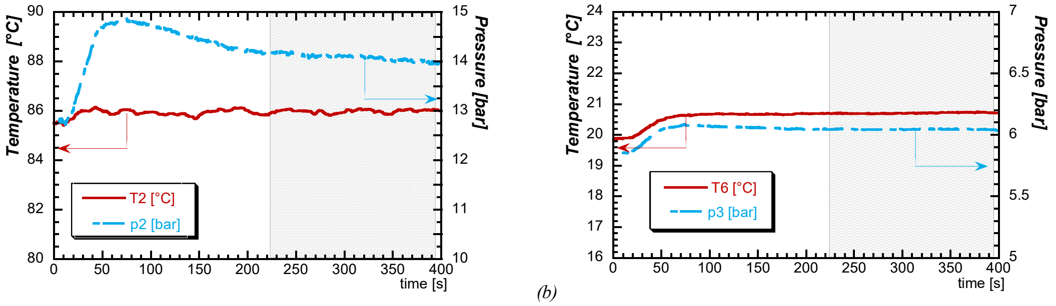
$$\delta_{f,i}^2 = \lambda_3 (x_i - x_{i-1})^2 + (1-\lambda_3)\, \delta_{f,i-1}^2 \qquad (5); \qquad s_2^2 = \frac{\delta_{f,i}^2}{2} \qquad (6)$$

where λ_2 and λ_3 represent filter factors. Larger λ values mean that fewer data are involved in the analysis, which has a benefit of reducing the time for the identifier to catch up to a process change. But, larger λ values increase the variability on the statistic and confounding interpretation. On the other side, lower λ values undesirably increase the time to identify a process change, but the precision increases [4]. In this study, the filter factors have been set equal to λ_1=0.2, λ_2=0.1 and λ_3=0.1, as suggested in [4].

At each time step, the calculated *R* value is compared to a critical value $R_{critical}$, to evaluate if the system is operating at steady-state or transient-state conditions: when $R < R_{critical}$ over a predefined time period, this time period can be considered as steady state. The statistical threshold of decision is chosen according to the physical description of the process and a preliminary data analysis.

The *R-test* method has been here applied to the ORC mass flow rate and to all ORC measured temperature and pressure variables acquired with sensors of Figure 1. The ORC steady state occurrence, after a change in a set-point, is declared when all selected variables, directly measured along the ORC circuit, reach stable condition in terms of the *R-test*, over a predefined time window.

For example, Figure 2 presents the organic fluid max and min temperature variables (T_2 and T_6) and the expander inlet and outlet pressure (p_2 and p_3) in a time window of a selected test, carried out with constant hot source temperature set point (equal to 85°C). The shown quantities have been identified as key variables representative of the ORC thermodynamic operation, i.e., T_2 and T_6 values depend on the hot and cold source respectively, p_2 is influenced by the ORC pump set-point regulation, while p_3 is also related to the condenser. More in detail, Figure 2 shows the key variables variation caused by a sudden increasing step of the ORC pump rotational speed set-point. Figure 3 shows the calculated time profile of the *R* parameter, for each of the selected key variables. A steady state operating condition can be declared in the highlighted time interval (shown in grey in figures), when the *R* values drop below a given $R_{critical}$. On the basis of a preliminary analysis of the ORC behavior in several performed tests with various set-point changes, the value $R_{critical}$=12 appeared to be a good threshold; this value has been identified for the ORC in study, by considering the transient behavior of both temperature and pressure. Moreover, Figure 3 highlights how the ORC highest temperature T_2 results a limiting quantity, strongly influenced by the hot source temperature behavior, while the R values evaluated for T_6, p_2 and p_3 result more stable in the presented time interval.



(a) (b)

Figure 2 - ORC key variables in a time window: *(a)* max temperature & expander inlet pressure; *(b)* min temperature & expander outlet pressure

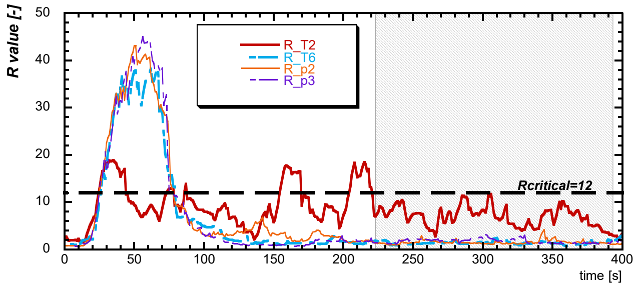


Figure 3 - R values vs time of ORC key quantities

4.1. Steady state operational points

An experimental campaign has been carried out in order to measure ORC thermodynamic performance at different hot source set-point conditions, after steady-state is reached. In the framework of a post processing analysis, all the measured and calculated instantaneous data acquired during various tests, have been averaged in the identified steady-state intervals. The minimum considered time widow was 100 seconds, while smaller intervals have not been considered for data collection. Table 2 lists all the averaged values of the measured quantities for three selected steady-state intervals of the set-point (SP in table). The selected operational points are characterized by similar values of cold source temperature T_{12}, organic fluid mass flow rate $\dot{m}_{ORC}$ and ORC max pressure p_2, as reported in Table 2.

The obtained hot source temperature T_{10} and the ORC max temperature values T_2 are close to the SP conditions. The cold source condition affects the value of the ORC minimum pressure p_6 (similar to p_5 and p_3 except for the pressure drops through the heat exchangers); the maximum pressure p_2 (similar to p_8 and p_9) depends on the ORC pump rotational speed regulation (in the performed tests it was progressively varied up to a fixed set value), which in turns directly affects the $\dot{m}_{ORC}$ value.

Table 2 – Experimental averaged measured data for three different steady-state Set-Points

Steady state	***#1***	***#2***	***#3***
SP [°C]	*65*	*75*	*85*
T_{10} *[°C]*	64.7	74.5	86.8
$\dot{v}_{10}$ *[l/s]*	2.63	2.63	2.65
T_{12} *[°C]*	17.9	17.7	17.6
$\dot{v}_{12}$ *[l/s]*	2.79	2.86	2.75
$\dot{m}_{ORC}$ *[kg/s]*	0.10	0.10	0.09
T_2 *[°C]*	64.6	73.8	86.0
T_3 *[°C]*	41.7	51.2	63.8
T_5 *[°C]*	24.3	24.7	25.6

Steady state	***#1***	***#2***	***#3***
SP [°C]	*65*	*75*	*85*
T_8 *[°C]*	23.0	22.9	23.1
T_9 *[°C]*	34.5	40.35	47.9
p_2 *[bar]*	14.3	14.4	14.1
p_3 *[bar]*	6.16	6.09	6.05
p_5 *[bar]*	6.02	5.95	5.92
p_6 *[bar]*	6.01	5.94	5.91
p_8 *[bar]*	14.3	14.4	14.1
p_9 *[bar]*	14.3	14.4	14.1

Figure 4 shows the thermodynamic cycle on the *T,s* diagram for R134a, obtained in the three selected steady-state set-point conditions; the hot and cold source temperature drops in the evaporator and condenser are also shown. It can be seen that T_2 is very close to the hot source max temperature (difference is within the range of 1°C); due to the similar p_2 values, the different hot source set-points cause different ORC superheating degree.

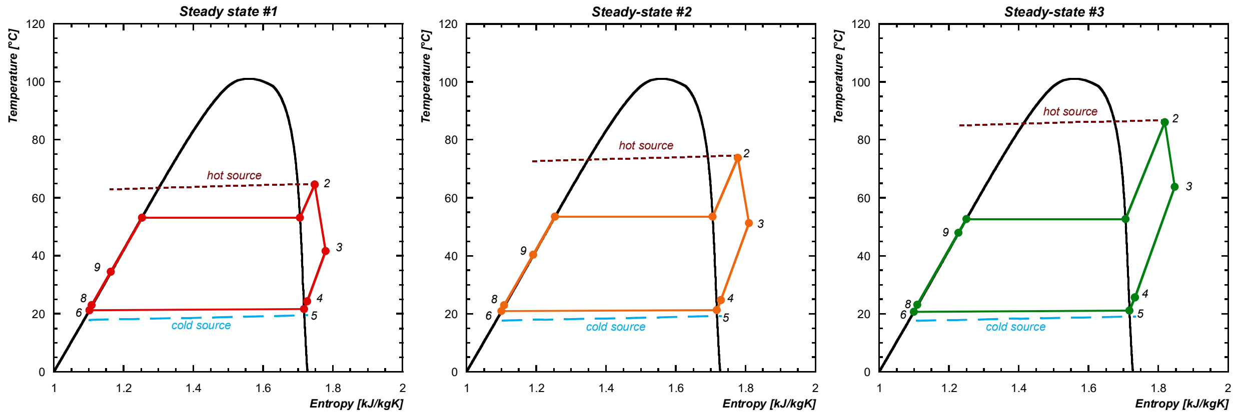


Figure 4 – *T-s* diagram of the cycle, based on averaged values during steady-state conditions for three different hot source temperature set-points

5. Performance indexes and preliminary results in selected steady-state conditions

Table 3 reports the averaged electric power P_{el} produced by the ORC in the selected steady-state conditions and the correspondent expander enthalpy variation Δh_{EXP}. Steady state #2 presents a higher value of P_{el} compared to #3, due to a higher value of $\dot{m}_{ORC}$ (see Table 2), despite a lower expander enthalpy variation. Various efficiency definitions have been considered to compare the steady-state operational points; the selected indexes are defined as in eqs. (7-10):

$$\eta_{ORC} = \frac{P_{EXP}}{Q_{EVAP}} = \frac{P_{el}}{\dot{m}_{ORC} \cdot (h_2 - h_9)} \quad (7)$$

$$\eta_{iso,EXP} = \frac{P_{el}}{\dot{m}_{ORC} \cdot \Delta h_{EXPiso}} = \frac{P_{el}}{\dot{m}_{ORC} \cdot (h_2 - h_{2iso})} \quad (8)$$

$$\eta_{Carnot} = 1 - \frac{T_{Cold,min}}{T_{Hot,max}} = 1 - \frac{T_{12}}{T_{10}} \quad (9)$$

$$\eta_{II} = \frac{\eta_{ORC}}{\eta_{rrc}} = \frac{\eta_{ORC}}{1 - \frac{T_{Cold,min}}{T_{Cold,min} - T_{Hot,max}} \cdot \ln\frac{T_{Cold,min}}{T_{Hot,max}}} = \frac{\eta_{ORC}}{1 - \frac{T_{12}}{T_{12} - T_{10}} \cdot \ln\frac{T_{12}}{T_{10}}} \quad (10)$$

In particular, η_{ORC} represents the ORC gross efficiency, evaluated as the ratio between the electric power generated at the expander and the recovered thermal power at the evaporator; $\eta_{iso,EXP}$ is the expander isentropic efficiency, defined as the ratio between the electric power and the isentropic power (i.e. the ideal power considering an isentropic expansion); η_{Carnot} is a simple Carnot efficiency, evaluated with respect to the max and min external sources temperature values; and η_{II} is an irreversibility recuperation cycle efficiency, defined according to [8]. This parameter is the ratio between the ORC efficiency and the efficiency of an ideal reversible recuperation cycle η_{rrc}, made up of an isobaric heat absorption, an isentropic expansion and an isothermal compression. The introduced efficiency parameters have been evaluated for the identified steady-state points as collected in Table 3; the steady state #3, characterized by a highest superheating degree, presents the highest values of $\eta_{iso,EXP}$, η_{Carnot} and η_{ORC}, but the lowest value of η_{II}. Indeed, the superheating degree increase causes an increase of the cycle losses, as thermal dissipations along the cycle and pressure drops.

Figure 5 presents a comparison of the efficiency indexes, normalized with respect to the maximum values, for the considered steady state conditions.

Table 3 – Electric power, expander enthalpy variation and efficiency values in the considered steady state conditions

	SP [°C]	Δh_{EXP} *[kJ/kg]*	P_{el} *[kW]*	$\eta_{iso,EXP}$ *[%]*	η_{Carnot} *[%]*	η_{ORC} *[%]*	η_{II} *[%]*
Steady state #1	65	8.45	0.73	38.25	13.85	3.67	50.46
Steady state #2	75	9.45	0.79	38.92	16.34	3.98	46.02
Steady state #3	85	11.22	0.77	39.51	19.22	4.20	40.81

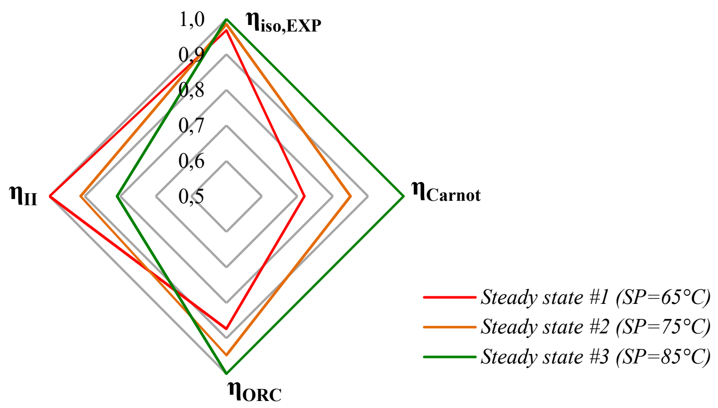


Figure 5 – Behavior of the normalized efficiency parameters

6. Conclusions

An experimental test facility has been developed to fully characterize the energy performance of a micro-ORC energy system. All temperature, pressure and mass flow values at the internal ORC system and in the external circuits are measured. All the available data are collected and used in real-time in order to evaluate the system performance through an *ad hoc* developed acquisition system. In this paper, a steady-state identification method has been selected, described and applied. The chosen *R-test* method offers a simple formulation for on-line application and showed a good efficacy in steady-state detection. For each observed variable, the method requires simple calculation of three filtered values, to be stored, and one comparison is required in each time-step. Therefore, this method has been implemented in the acquisition system for a real-time steady-state identification. The *R-test* method has been applied to a limited number of set-points, to elaborate the corresponding ORC performance. The organic fluid maximum temperature has been identified as the most critical quantity for steady-state detection. The results for the three considered set-points show how the increase of superheating causes an increase of the cycle efficiency, a slight increase of the expander efficiency, but also an increase of the cycle irreversibility. The steady-state detection method will be applied for a test campaign, investigating various operating points of the system.

References

[1] Macchi, E., and M. Astolfi. "Organic Rankine Cycle (ORC) Power Systems: Technologies and Applications." (2017).
[2] Landelle, Arnaud, et al. "Organic Rankine cycle design and performance comparison based on experimental database." Applied Energy (2017).
[3] Kim, Minsung, et al. "Design of a steady-state detector for fault detection and diagnosis of a residential air conditioner." International journal of refrigeration 31.5 (2008): 790-799.
[4] 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.
[5] Jiang, Taiwen, et al. "Application of steady-state detection method based on wavelet transform." Computers & chemical engineering 27.4 (2003): 569-578.
[6] 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.
[7] 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.
[8] Bianchi, M., and A. De Pascale. "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 88.5 (2011): 1500-1509.