ORC APPLICATIONS FROM LOW GRADE HEAT SOURCES

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ABSTRACT

The Organic Rankine Cycle (ORC) has been proven as an efficient way to benefit from low grade heat sources, with a great interest in waste heat recovery and use of renewable heat sources. In this way, this work deals about three different applications implemented in Spain. The first application consists of a power only system for industrial waste heat recovery, taking advantage from the exhaust air of a ceramic furnace to produce a rated electrical power of 20 kW. The second application is a Combined Heat and Power (CHP) system integrated as a bottoming power cycle of an Internal Combustion Engine (ICE), with the purpose to recover waste heat from exhaust gases. This system is installed in a hospital to increase the ICE electrical production and generate hot water up to 90 ºC. The third application can operate producing power only or heat and power. In this last case, the ORC module is used to profit thermal energy from a biomass supported solar thermal system and producing a maximum electrical power about 6 kW and hot water above 80 ºC.

Moreover, focusing on the ORC modules performance, experimental data obtained from tests developed under different operating conditions in the three application cases are analyzed and discussed.

1. INTRODUCTION

The ORC (organic Rankine cycle) has been proven as an efficient way for power generation from low grade heat sources (Yamada *et al.*, 2014). It is a similar power cycle to the steam Rankine cycle, but uses more volatile fluids instead of water to improve the efficiency in low temperature applications (Li *et al.*, 2012). Its operating principle consists of recovering the thermal energy from the heat source through the evaporation of the working fluid and reducing the enthalpy in an expander to produce mechanical work, which is turned into electricity by an electric generator. This is a closed system, which condenses the vapor from the expander outlet and pressurizes the liquid to restart the cycle again. So, it is considered a simple cycle that requires little maintenance, compared to other power cycles like Kalina (Bombarda *et al.*, 2010), Goswami, transcritical cycle or trilateral-flash cycle (Chen *et al.*, 2010); in addition to its mature and proven technology against direct conversion techniques (thermo-electric, thermionic or piezoelectric) (Tchanche *et al.*, 2011).

The application of ORC systems are mainly focused on renewable and waste heat sources, with several examples like: solar thermal (M. Wang *et al.*, 2013), geothermal (Franco, 2011), oceanic (Tchanche *et al.*, 2011), biomass (Algieri & Morrone, 2012), waste heat from power plants (Dolz *et al.*, 2012), waste heat from industrial processes (D. Wang *et al.*, 2012) or others (H. Wang*et al.*, 2011).

Moreover, the ORC systems can be used for combined heat and power applications. Thus, the ORC can be used as a power only generation system (Yamada *et al.*, 2014), recovering the thermal energy from the heat source to produce electricity with the maximum efficiency achievable and rejecting the thermal energy from the condenser to the cold side. On the other hand, the thermal energy from the condenser also could be produced with a profitable temperature for users, reducing the electrical efficiency of the system, but increasing its global efficiency (Dentice d'Accadia *et al.*, 2003). Thereby, the ORC operates as a combined heat and power (CHP) system, requiring lower primary energy consumptions compared to a separate heat and power production, besides reducing global energy costs and pollutant emissions to the atmosphere.

Regarding to the ORC use for power applications, various studies can be found in the literature. So, Zhou *et al.*(2013) tested an ORC for waste heat recovery from flue gases. The authors used a liquefied petroleum gas stove to simulate the heat source and to control the temperature in the range of 90 to 220 ºC. The working fluid selected was R123 and a scroll expander, obtaining a maximum power output of 0.645 kW and a cycle efficiency of 8.5 %. Bracco *et al.* (2013) tested a small-size ORC, that used R245fa as working fluid and a scroll expander, for waste heat recovery. The heat source was simulated using an electric boiler, achieving a cycle efficiency between 8 and 9 %. Casci *et al.*(1981) used an ORC, with a rated electrical power of 40 kW, in a ceramic kiln to profit from flue gas waste heat. Forni *et al.*(2012) summarized various analysis of an ORC manufacturer in cement, glass, steel and oil&gas industries. The net electrical production went from 7.6 to 39.2 GWh/y, allowing payback periods from 7.2 to 9.2 years.

With respect to the ORC use for CHP applications, a great interest has received for residential and commercial applications. In this way, Dong *et al.* (2009) reviewed small and micro-scale biomass-fuelled CHP systems, comparing the ORC to other conversion technologies. The researchers pointed that the ORC encounters technical and economical obstacles, in comparison to medium and large-scale systems, requiring to reduce the specific investment cost and increment the electrical and CHP efficiencies. Experimental results obtained in a preliminary investigation were presented by Farrokhi *et al.* (2014) about a gas-fired ORC-based micro-CHP system for residential buildings. Thereby, using isopentane as working fluid and a vane type of expander, a maximum electrical power output of 0.774 kW and a net cycle electrical efficiency of 1.66% were achieved. Similarly, Qiu *et al* .(2012) experimented with a biomass-pellet boiler and an ORC for micro-CHP applications, by heating to 46 ºC the cooling water of the condenser outlet. The main working fluid used was HFE7000 and, again, a vane type of expander. So, 0.861 kW were generated with a gross electrical efficiency of 1.41% and a CHP efficiency of 78.69%. Declaye *et al.* (2013) characterized an oil-free scroll expander using R245fa as working fluid, showing that the cycle could produce up to 50 ºC of useful heat, a maximum shaft power of 2.1 kW and mechanical efficiency of 8.5%.

From the reviewed information, different applications and uses for the ORC can be observed. However, few works address the final application of the ORC and its experimental performance when a commercial module is used. In this way, this work deals about three different ORC applications implemented in Spain. The first application consists of using an ORC as a power only system, the second one uses the ORC as a CHP system and the last application was designed to operate with the ORC in both modes, power only and CHP. Thereby, these applications are addressed in this paper. Moreover, experimental data obtained from the tests developed in each ORC module are exposed and discussed.

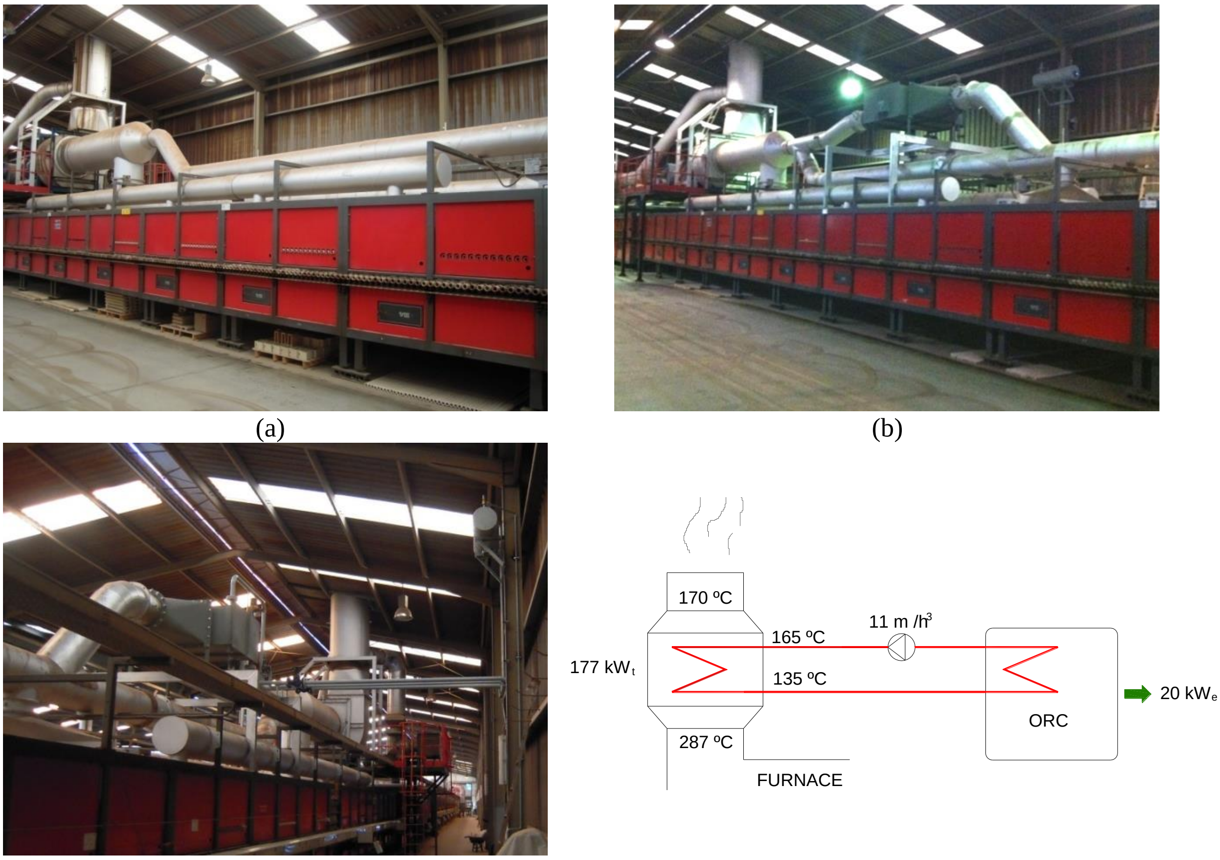
For this purpose, the rest of the paper is organized as follows. Section 2 presents the three application cases. Section 3 describes the main characteristics of the ORC modules. Section 4 exposes the main results of the experimental characterization. Finally, Section 5 summarizes the main conclusions of the work.

2. APPLICATIONS DESCRIPTION

This section describes the three applications addressed in this work.

2.1 Power only application

This application consists of profiting waste heat from exhaust gases of a ceramic furnace. Specifically, recovering the waste heat available in the indirect cooling air, which are clean gases with high temperature, due to its proximity to the furnace burners the furnace. The recovery facility is mainly composed by a recuperator heat exchanger, located in a bypass of the cooling air duct, and a heat transfer loop with thermal oil that transports the thermal energy from the heat source to the ORC module, as Fig. 1.a to Fig. 1c show. Moreover, Fig. 1.d shows the scheme of the facility.



(a) (b)

(c) (d)

Figure 1: Industrial furnace of Keros Ceramica and heat recovery facility: (a) original facility, (b) modified facility, (c) heat transfer loop, (d) facility scheme.

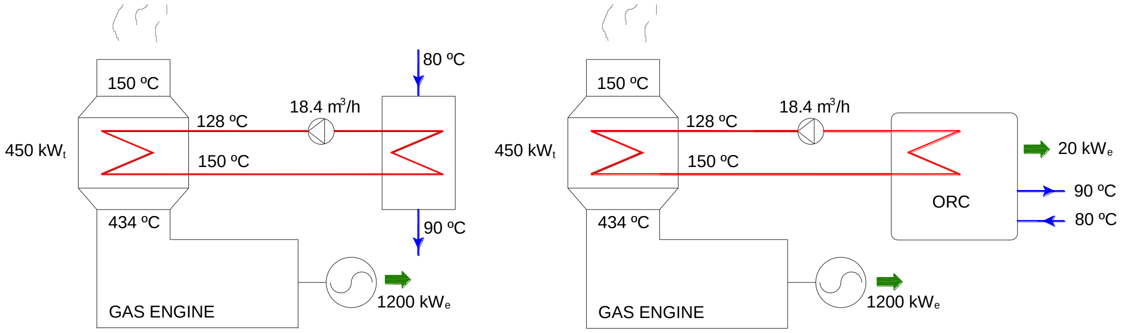
The main features of the recuperator heat exchanger are listed in Table 1. This heat exchanger was designed to recover a thermal power of 177 kW from the heat source and provide thermal oil at 165 ºC to the ORC module.

Table 1: Recuperator heat exchanger features.

Thermal capacity (kW)	177
Air volumetric flow rate ($Nm^3 \cdot s^{-1}$)	1.15
Air temperatures (ºC)	287/170
Oil temperatures (ºC)	135/165
Air pressure drop (mbar)	1.90
Thermal oil pressure drop (bar)	0.8
Surface (m^2)	65.6

2.2Combined heat and power application

The original facility consisted of an Internal Combustion Engine (ICE) for a CHP application in a hospital located in Ourense (Spain). This ICE was designed to provide a rated electrical power of 1,200 kW and up to 400 kW of useful heat from the exhaust gases, as Fig. 2.a represents. Then, the aim of the project was to replace the heat exchanger by an ORC system, producing a similar useful heat, at the same temperature of 90 ºC, and more electricity, as Fig. 2.b represents.



(a) (b)

Figure 2: Heat source of the ORC system: (a) scheme of the original facility with heat exchanger, (b) scheme of the improved facility through ORC.

The main features of the recuperator heat exchanger, integrated in the chimney, are listed in Table 2. This heat exchanger was designed to recover a thermal power of 450 kW from the heat source and provide pressurized water at 150 ºC to the ORC module.

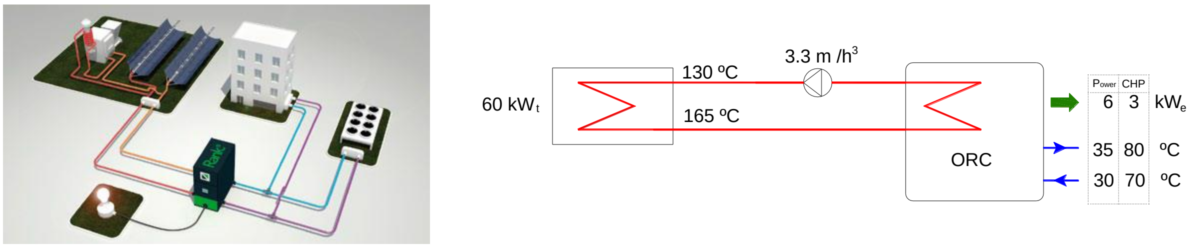
Table 2: Recuperator heat exchanger features.

Thermal capacity (kW)	450
Exhaust gas flow rate (kg/h)	5,191
Exhaust gas temperatures (ºC)	434/150
Pressurized water temperatures (ºC)	128/150
Exhaust gas pressure drop (mbar)	17
Pressurized water pressure drop (mbar)	50
Surface (m^2)	76

2.3 Power and CHP application

This system was designed to operate with renewable heat sources, specifically a biomass supported solar thermal system. Thus, the ORC should operate efficiently in both modes, power only generation and CHP production.

A typical architecture of the facility in which the ORC is integrated is illustrated in Fig. 3.a. Fig. 3.b shows the scheme of the facility. Furthermore, the design specifications from customers of this module are listed in Table 3.



(a) (b)

Figure 3: Power and CHP applications: (a) typical architecture, (b) facility scheme.

Table 3: Design specifications.

Thermal power input (kW)	60
Thermal fluid	Oil or Water-glycol (10%)
Inlet temperature of the thermal fluid (ºC)	165
Inlet temperature of cooling water in generation mode (ºC)	30
Inlet temperature of cooling water in CHP mode (ºC)	70

3. ORC MODULES DESCRIPTION

This section describes the main characteristics of the ORC modules, shown in Fig. 4, addressing the cycle configuration, working fluid, expander and dissipation system.

(a) (b) (c)

Figure 4: ORC modules: (a) Power generation system integrated in the industrial application, (b) CHP system during tests, (c) Power only and CHP system during tests.

3.1 Cycle configuration and working fluid

All the ORC systems used in these applications are commercial modules from Rank®, whose main characteristics are summarized in Table 4. In these studied cases, the modules employ the same architecture and use the same working fluid. Regarding to the architecture, the regenerative configuration is used. This configuration allows recovering the thermal energy from the heat source, besides the waste heat from the expander outlet to preheat the liquid, improving the cycle electrical efficiency. The working fluid used is R245fa, commonly used among ORC manufacturers (Vélez *et al.*, 2012) and the researches reviewed. This is a non flammable fluid with low toxicity and moderate environmental properties, which also has been proven as an efficient fluid for low grade waste heat recovery (Peris *et al.*, 2013). However, the characteristics of the expander differ in function of each application.

Table 4: Main characteristics of the ORC modules used.

Cycle configuration	subcritical, regenerative with superheating
Working fluid	R245fa
Expander technology	volumetric
Heat exchangers type	brazed plate
Maximum operating temperature (ºC)	170
Maximum dissipating temperature (ºC)	90

3.2 Expander

The ORC modules use rotary volumetric expanders, whose sizes, speeds and volume ratios (Vi) have been optimized to achieve the maximum efficiency during the operating point, established as design conditions. In this way, Table 5 collects the maximum efficiency ($\varepsilon_{el,\ ise}$) of the expanders and the pressure ratio (r_p) in which it was achieved. As it can be seen, the ORC designed for the power application operates efficiently at a high pressure ratio (Peris *et al.*, 2015a). In contrast, the ORC designed for the CHP application only operates efficiently at low pressure ratios. On the other hand, the third application can operate with an intermediate efficiency in both modes, being a suitable solution for a flexible system.

Table 5: Experimental expander efficiencies and its associated pressure ratios.

	$\varepsilon_{el,ise}$ (%)	r_p	References
Power application	64.89	7.93	(Peris *et al.*, 2015b)
CHP application	68.54	2.61	(Peris*et al.*, 2015c)
Power and CHP	63.77	4.10	(Peris*et al.*, 2015d)

3.3 Dissipation system

The dissipation system varies in function of the type of application. So, in a power application the thermal energy from the condenser is rejected to the ambient. For this, the dissipation system was directly implemented through an air condenser, previously shown in Fig. 4.a. This system allows reducing exergetic losses compared to a dry cooler with cooling water, besides simplifying the scheme, since there is not required another pump nor its associated safety and control devices.

On the other hand, in a CHP application the thermal energy from the condenser is considered as useful heat for users. So, the hot water from the outlet of the condenser could directly feed consumers. In order to simulate this consumption, a dry cooler with cooling water was used during tests. Thereby, reducing the dry coolers fans velocity, the condensing temperature was controlled. So, both modes, power, with fans at full velocity, and CHP, with fans at reduced velocity, were simulated during tests. The dissipation systems used in the tests are shown in Fig. 5.

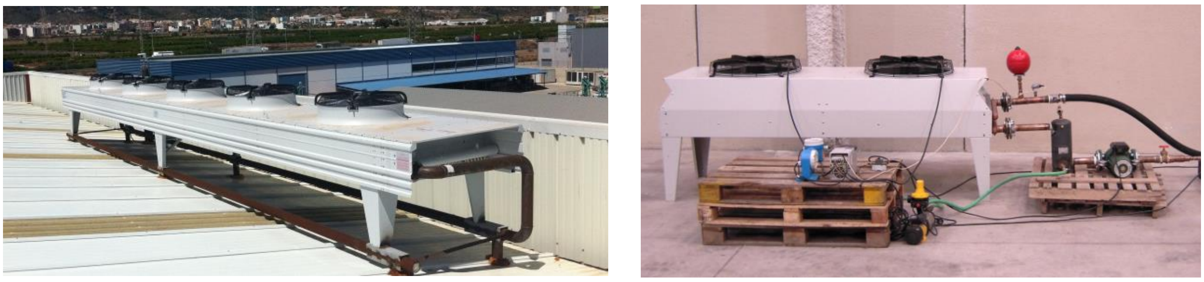
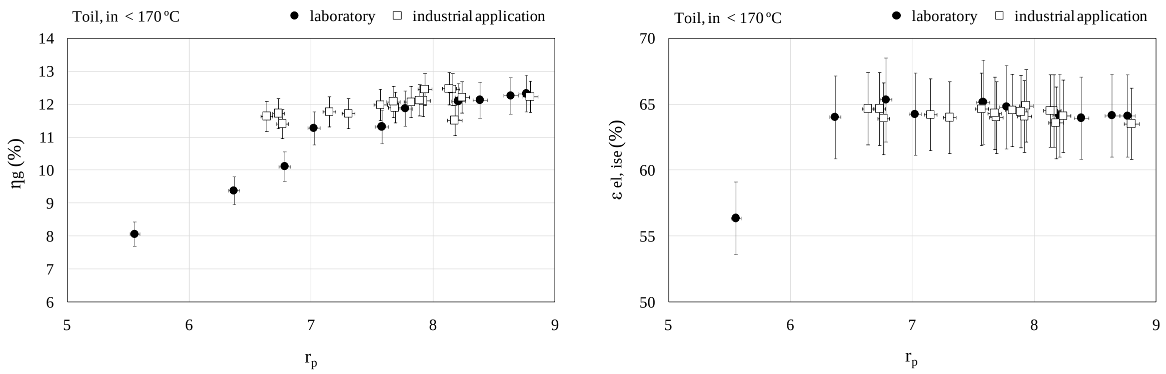

(a) (b)

Figure 5: Dissipation systems: (a) CHP system, (b) power and CHP system.

4. RESULTS

In this section, the gross electrical efficiency of the cycle (η_g) and the expander electrical isentropic effectiveness ($\varepsilon_{el,\ ise}$) obtained during tests are presented and discussed.

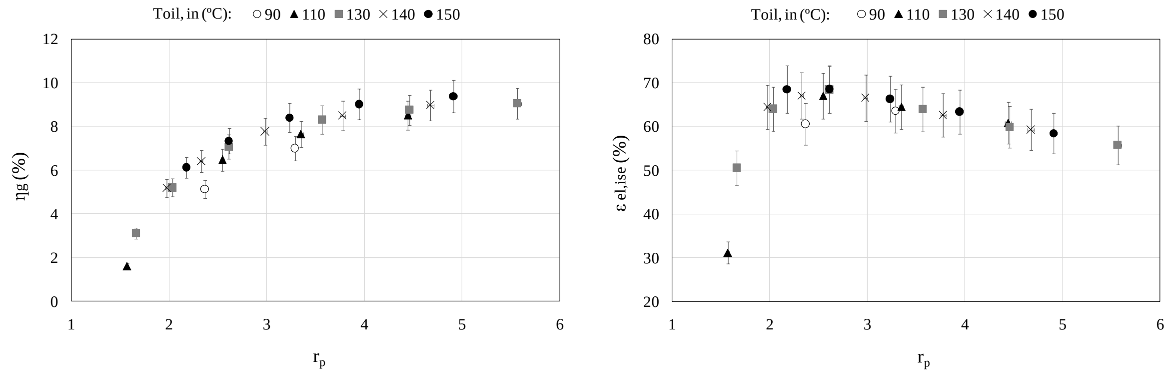
Regarding to the ORC for power applications, Fig. 6.a shows that a maximum gross electrical efficiency of 12.47% is obtained. This efficiency is reached with a pressure ratio about 8, being a system optimized for its operating conditions. Moreover, Fig. 6.b shows that the expander operates with a stable effectiveness for high pressure ratios.



(a) (b)

Figure 6: ORC for power applications: (a) gross electrical efficiency, (b) expander electrical isentropic effectiveness.

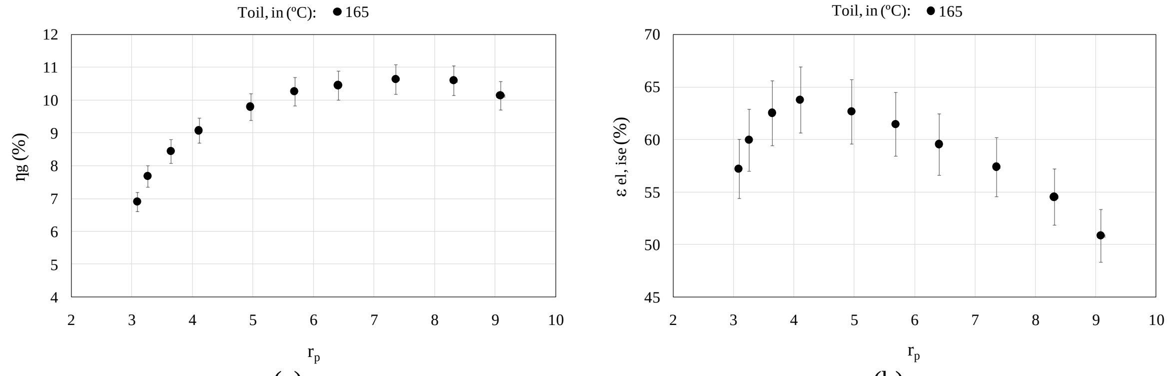
Regarding to the ORC for CHP applications, Fig. 7.a shows that a maximum gross electrical efficiency of 9.40% is obtained. This low value, compared to the latter, is mainly due to the different expander used. So, Fig. 7.b shows that the expander is optimized for a pressure ratio between 2-3, which is a suitable value to operate in CHP applications, but a poor value for power only generation.



(a) (b)

Figure 7: ORC for CHP applications: (a) gross electrical efficiency, (b) expander electrical isentropic effectiveness.

As it has been said above, the third application was designed using an expander with an intermediate Vi, that allows the operation in both modes, power only and CHP. Thereby, Fig. 8.a shows that the maximum value of electrical efficiency remains between the two previous ORC systems, with a maximum of 10.64%. The electrical effectiveness of the expander was maximized for a pressure ratio above 4, as Fig. 8.b shows, being a module suitable to operate with a moderate efficiency in both modes, but not optimized in comparison with the previous two modules.



(a) (b)

Figure 8: ORC for power and CHP applications: (a) gross electrical efficiency, (b) expander electrical isentropic effectiveness.

5. CONCLUSIONS

This work deals about three different applications developed using ORC systems in Spain. For this, the heat source, dissipation system and the main characteristics of the ORC are addressed. Moreover, the main results of the experimental characterization of each module are presented and analyzed.

In this way, the results show that the expander plays a key role in the optimization of a system for a specific application. So, a large Vi is recommended to operate in power applications, demonstrating a gross electrical efficiency of 12.47% with activation temperatures about 165ºC. A small Vi is preferable for CHP applications, being able to provide hot water up to 90 ºC with an acceptable gross electrical efficiency of 9.40%, with activation temperatures about 150ºC. However, if the system requires operating in both modes, power and CHP, an intermediate Vi results a suitable solution. So, the experimental data show a maximum gross electrical efficiency of 10.64% with activation temperature about 165ºC.

NOMENCLATURE

ε	effectiveness	(%)
η	efficiency	(%)
r_p	pressure ratio	
Vi	built-in volume ratio	

Subscripts

el	electrical
g	gross
ise	isentropic

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ACKNOWLEDGEMENT

The authors are indebted to the Minister of industry of ‘GeneralitatValenciana’ (Spain) for its financial assistance under project INIDIV2010022 and Rank®, the ORC manufacturer, for its support in this project. Also to thank greatly the Jaume I University for its financial support under the PhD grant PREDOC/2013/28 of ‘Convocatòriad'ajudespredoctorals per a la formació de personal investigadordelPla de promoció de la investigació de la UniversitatJaume I de Castelló (Spain)’.