SMALL SCALE ORC DESIGN FOR A COGENERATION SOLAR BIOMASS SUPORTED APPLICATION

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ABSTRACT

Combined Heat and Power (CHP) systems and bottoming power cycles for waste heat recovery have received considerable attention over the past decades. Among the several proposed power cycles, the Organic Rankine Cycle (ORC) has been attracting increasing attention. ORCs have been proved as a feasible technology for low temperature (< 250 ºC) and small scale (< 1 MW) applications, converting renewable energy into heat and power.

The aim of this work is to present the design process of a micro scale ORC (< 100 kW), suitable for a Combined Cold, Heat and Power (CCHP) application, through an adsorption chiller, that uses solar biomass supported renewable energy as heat source. The ORC module has to be designed in order to work in cogeneration mode and generation mode (power only).

Therefore, this work deals with the preliminary design of the ORC module, including working fluid and configuration selection, from the technical requirements of the equipment imposed by the application. The optimization of the operating conditions is also addressed in order to maximize the efficiency of the system. Finally, an expander has been proposed and characterized. The experimental results from the expander have been used in order to predict the expected behavior of the ORC module in cogeneration mode, producing hot water up to 70ºC.

1. INTRODUCTION

Due to environmental constrains, Combined Heat and Power (CHP) systems and bottoming power cycles for waste heat recovery have received considerable attention. Several power cycles have been proposed for low temperature heat recovery. Among them, the Organic Rankine Cycle (ORC) has been attracting considerable attention (Vélez, 2012). Several ORC systems have been installed for recovering waste heat from power plants (Dolz *et al.*, 2012), industrial processes (Peris *et al.*, 2015a) or from internal combustion engines (Peris *et al.*, 2013). ORC systems have also been widely used for converting renewable energy, such as solar (Wang *et al.*, 2013), biomass (Huang *et al.*, 2013) and geothermal (El-Emam and Dincer, 2013) energy into power. ORCs have been studied by various authors, commonly classifying heat sources with temperatures ranging between 100ºC and 250ºC as "low temperature" heat sources and above 250ºC as "high temperature" heat sources. Brasz *et al.* (2005) considered low temperature applications and Zabek *et al.* (2013) studied waste heat recovery at high temperatures, demonstrating ORC feasibility in both cases. Focusing on residential and commercial applications, the ORC has been proposed as a suitable energy conversion technology, since it can achieve great efficiencies from low grade heat sources and can result cost-effective for small scale and micro-scale applications, often referred to an electrical power lower than 1 MW and 15 kW, respectively (Peris *et al.*, 2015b).

The choice of the ORC working fluid has an important influence on the system efficiency, and numerous works on this subject can be found in the literature. Lai *et al.* (2011) investigated potential single-component working fluids for high temperature ORC processes and found that siloxanes and selected hydrocarbons are promising. Shale *et al.* (2007), Shengjun *et al.* (2011) and Quoilin *et al.* (2011) evaluated various working fluids for low to medium temperature applications, highlighting that hydrofluorocarbons with low critical temperatures, such as HFC-134a and HFC-245fa, are suitable. Molés *et al.* (2014) predicted attractive thermodynamic performance of ORC systems for low temperature heat sources using HCFO-1233zd-E and HFO-1336mzz-Z as low Global Warming Potential (GWP) alternatives to HFC-245fa.

About cycle configuration, different suitable configurations for low grade heat sources recovery using ORCs can be found in the literature. One of the most commonly used is the regenerative ORC, which can be performed in three ways: with an internal heat exchanger (Wang *et al.*, 2013), with open and closed feed fluid heaters using turbine bleeding (Gang *et al.*, 2010) or using a vapor injector as a regenerator (Xu and He, 2011). Another configuration proposed for low grade heat sources is based on superheating the fluid in a single stage (Roy *et al.*, 2011) or through various reheat stages (DiGenova *et al.*, 2013). Two pressure levels and the use of an ejector have been also studied by Li *et al.* (2012), increasing the output capacity compared to the basic ORC. Finally, transcritical configurations have been also proposed to allow a better temperature matching with low irreversibilities (Ho *et al.*, 2012), generally requiring higher operating pressures.

Regarding expander technology, Peris *et al.* (2015c) indicated that the volumetric expander type is most appropriate for low grade heat sources and micro-scale application. The reason is that volumetric expanders results more appropriate than turbomachines, as they are characterized by lower flow rates, higher pressure ratios, much lower rotational speeds, besides to exhibit good effectiveness and tolerate liquid phase during expansion (Quoilin, *et al.*, 2013). In this way, recent works continues improving volumetric expanders, such as rotary volumetric expanders based on the Wankel concept (Antonelli *et al.*, 2014), scroll (Song *et al.*, 2014) or screw expanders (Zhu *et al.*, 2014). Furthermore, an appropriate operating pressure ratio for the expander, a suitable working fluid and an efficient configuration are also recommendations to increase the electrical gain (Peris *et al.*, 2013).

The aim of this work is to present the design process of a small scale ORC, suitable for a Combined Cold, Heat and Power (CCHP) application that uses solar biomass supported renewable energy as heat source. So, the work presents the technical requirements of the equipment imposed by the application, discusses the working fluid selected, reports the thermodynamic cycle, presents the experimental characterization of an expander prototype and, finally, summarizes the main conclusions.

2. TECHNICAL REQUIREMENTS

The technical requirements of the equipment imposed by the application are the boundary conditions that constrain the design process of the ORC system. The overall scheme of the system is presented in Figure 1. The cogeneration unit is planned to work on two different operating modes: generation mode and cogeneration mode.

Attending to the renewable heat source activation, it consists on a solar biomass supported heat source. The heat transfer fluid will be thermal oil. The solar collectors will work at temperatures up to 270ºC, but the thermal oil inlet temperature into the ORC is expected to be, due to buffers/collectors and thermal losses, up to 245ºC. In order to maintain fixed the inlet temperature on the ORC, a buffer tank is required to avoid the solar field disturbances.

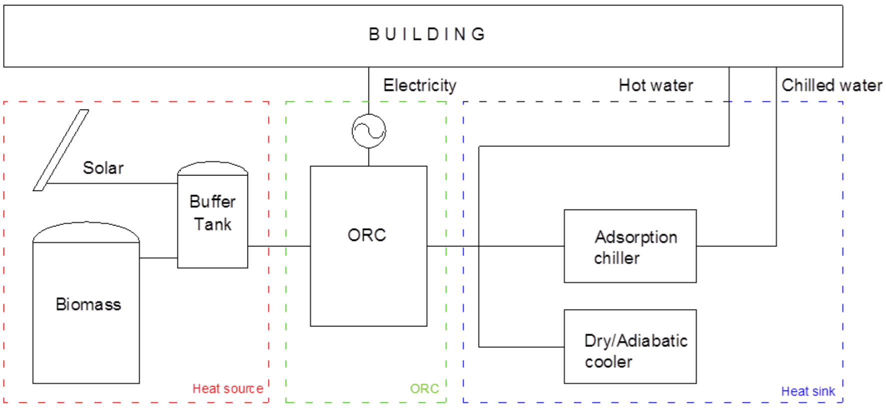


Figure 1: Overall scheme of the system

Regarding the heat sink, the different modes of the cogeneration unit result in two different condensation temperatures, fixed by the heat sink transfer fluid temperatures, in the ORC: 30ºC for generation mode and 70ºC for cogeneration mode. In generation mode the condensation heat is rejected to the ambient through a dry/adiabatic cooler. In cogeneration mode the heat sink is used to produce hot water for heating or hot water to activate an adsorption chiller. Water has been selected as the heat transfer fluid for the heat sink loop.

3. WORKING FLUID

The working fluid is a key parameter that determines the operating pressures, maximum allowable temperature, system efficiency, optimal configuration and components technology. So, it has a great influence on achieving the target. Furthermore, there are other criteria to be considered in the working fluid selection, such as security characteristics (toxicity and flammability) and environmental issues (ODP and GWP). In ORC systems with high temperature heat sources, working fluids as toluene, hydrocarbons or silicone oils are used. However, looking for security and environmental characteristics with high efficiencies at low temperatures, the following fluid families have been considered: hydrofluorocarbons (HFC), hydrofluroether (HFE), and hydrofluoroolefins (HFO).

Table 1: working fluid candidates properties

Fluid	**Toxicity PEL (ppm) / Flammability**	**GWP**	**ODP**	**T_{crit} (ºC)**	**P_{crit} (bar)**	**T_{max} (ºC)**
HFC-134a	1000/Non-flammable	1300	0	101	40.59	<200
HFC-245fa	300/Non-flammable	950	0	154	36.51	<250
SES36	1000/Non-flammable(*)	3710	0	177.55	28.49	190
HFO-1234yf	500/Low-flammability	4	0	94.7	33.82	<200
HFO-1234ze(Z)	500/Non-flammable	1	0	150	35.30	<200
HCFO-1233zd-E	300/Non-flammable	5	0	165.6	35.71	200
HFO-1336mzz-Z	500/Non-flammable	9	0	171.3	29	<250

Different working fluid options have been analyzed and evaluated for their application in the current application based on the suitable fluids found in the literature. Special attention has been taken in security properties, as toxicity and flammability, thermal stability and environmental properties, like Global Warming Potential (GWP) and Ozone Depletion Potential (ODP). Relevant thermo-physical properties of the working fluid candidates are summarized in Table 1.

Maximum allowable temperature supposes another constrain in order to avoid degradation in the working fluid. So, HFC-134a, SES36, HFO-1234yf and HCFO-1233zd-E have been discarded. HFO-1336mzz-Z is not commercially available nowadays, despite its desirable properties, as low GWP, among others. Finally, HFC-245fa has been selected as the best available working fluid candidate, with low toxicity, no flammable, maximum allowable temperature below 250ºC (240ºC) and good expected efficiencies. HFC-245fa is commonly selected as working fluid for similar heat sources when safety levels and environmental impacts are considered (Wang *et al.*, 2011).

4. THERMODYNAMIC CYCLE

In the framework of a systematic investigation approach, various possible modifications to the simple ORC plant layout are analyzed and compared, in order to improve the ORC recovery performance; arrangements such as recuperation, superheated cycle, transcritical conditions, regenerative cycle and their combinations are taken into account.

From the analysis of the different options for the configuration of the ORC cycle, the most suitable of them, for the range of operating conditions of the targeted application, have been investigated. The adoption of a recuperative heat exchanger has been considered, due to the high temperature of the heat source compared with the critical temperature of the working fluid selected, having to work with high superheat degree. The possibility of working in transcritical conditions has been studied to allow a better temperature matching with low irreversibilities, although generally requiring higher operating pressures and more pump consumptions. Therefore, various cycles are proposed, showing their schemes in Figure 2.

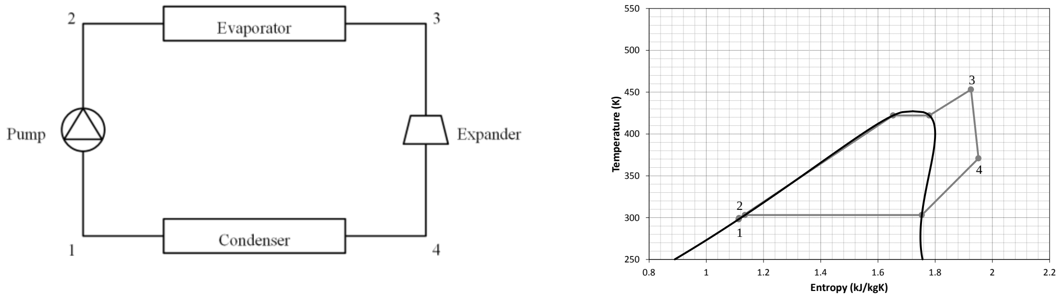
After the analysis of the configurations proposed, the possibility of working in transcritical conditions has been rejected due to the increase on the pump consumption that reduces the net efficiency of the cycle. The increase on the pump consumption due to the transcritical operation can suppose, depending on the operating conditions, a 10% of the gross power produced by the expander, higher in comparison with the 5% of the pump consumption in subcritical operation. The adoption of a recuperative heat exchanger has been selected, due to the improvement on the efficiency by reducing the thermal power required. The adoption of a recuperative heat exchanger improves the efficiency between 12.5% and 31.5%, depending on the operating conditions. Finally, the best configuration is the use of a recuperative heat exchanger in subcritical conditions. This configuration has been previously selected as optimal for HFC-245fa as working fluid with similar heat source conditions for Branchini *et al.* (2013).

5. EXPERIMENTAL APPROACH

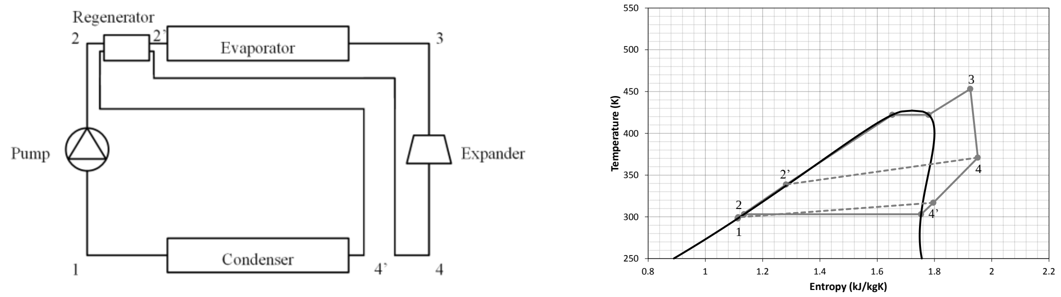
With the working fluid, configuration and operating conditions selected, the next step has been the selection of the components of the ORC module and their design. Knowing that the expander is a key parameter on the ORC efficiency, its design has been addressed constructing and testing various prototypes.

The expander technology selected to meet the prototype requirements has been analyzed and a volumetric expander is proposed. As previously introduced, the volumetric technology shows better results for low grade heat sources and small scale applications. So, the volumetric technology has been adopted for the expander design.

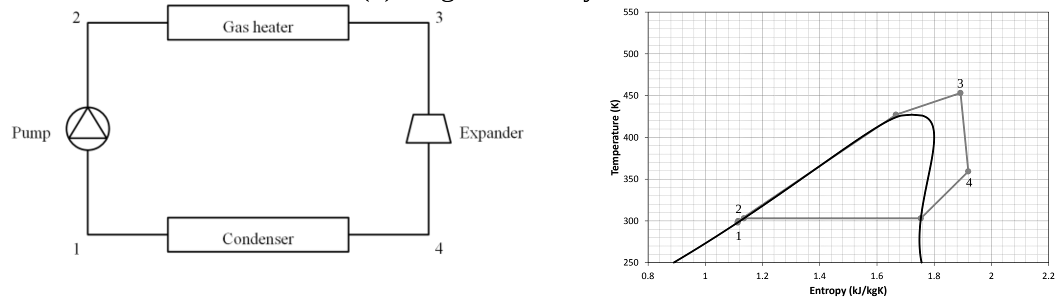
The main challenge in the expander design is the different operating conditions presented in generation and cogeneration mode, taking into account the maximum temperature allowable at the expander inlet of 240ºC. In this way, different designs are analysed looking for optimizing the efficiency of the system in all the range of expected operating conditions, not only the electrical efficiency but also cost, size, weight, flexibility… Therefore, two different designs are considered, one specially designed for optimizing generation mode and the other looking for optimal energy profit in cogeneration mode.



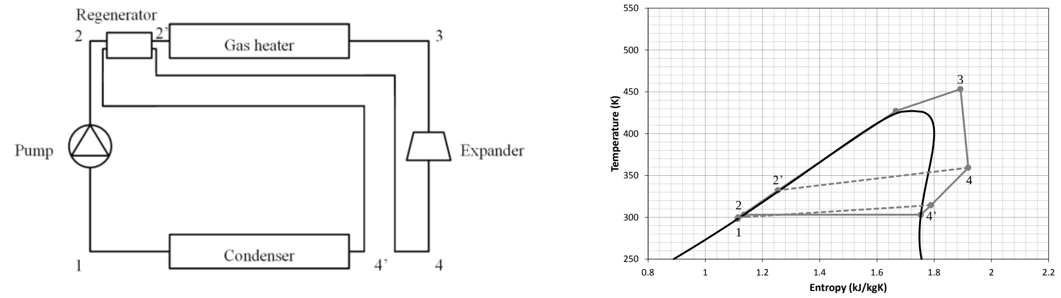
(a) Basic cycle - subcritical



(b) Regenerative cycle - subcritical



(c) Basic cycle - transcritical



(d) Regenerative cycle - transcritical

Figure 2: Configurations proposed

The design optimized for generation mode achieves a good efficiency condensing below 30ºC but it is highly penalized above 40ºC of condensing temperature and, besides, has serious disadvantages as high cost, control handicaps, high size and weight, making the future product non feasible. On the other hand, the expander design optimized for cogeneration mode presents the best efficiency in cogeneration mode and, although it is slightly penalized in generation mode, it shows a good performance in the operating range (for the expected range of condensing temperatures) and being a cost-effective solution with the advantage of reducing considerably size and weight and simplifying ORC control.

Figure 3: Simulated and constructed prototype and the ORC test bench

Finally, the expander prototype has been designed according to the second proposal, optimizing the cogeneration mode, since the overall efficiency in this mode is much higher than in generation mode and due to the advantages exposed before. The expected performance of this expander prototype has been experimental tested in the test bench constructed ad-hoc for the expander tests. Thermal and electrical power haven been scaled down to meet the disposal thermal power on the test bench, with a 1:3 scale.

In the following, the main parameters measured of the test bench are presented. Firstly, the thermal power input is monitored in the hot side through inlet and outlet thermal oil temperatures, using surface thermocouples, and the thermal oil volumetric flow rate, that is measured using a vortex flow meter. The working mass flow rate is obtained through a Corioliss mass flow meter. The pressure and temperature at the inlet and outlet port of the expander are measured for monitoring its performance. Furthermore, its electrical power output is measured using a wattmeter located at the electric generator, while the pump electrical consumption is measured in the electric motor through another wattmeter.

The measuring devices uncertainties, extracted from manufacturer's data sheets, and the calculated parameters uncertainties, obtained as a function of the uncertainty on each measured variable by using the RSS method (Taylor, 1997), are collected in Table 2.

Table 2: uncertainties of measured and calculated parameters

Parameter	**Uncertainty**
Temperature (ºC)	1
Pressure (%)	0.5
Mass flow rate (%)	0.3
Thermal oil volumetric flow rate (%)	0.75
Electrical power (%)	1.2
Electrical isentropic effectiveness (%)	4.89
Pressure ratio (%)	0.71

For the analysis of the experimental data obtained during tests, the performance of the expander is defined as the electrical expander effectiveness by Eq. 1, often also named expander overall efficiency. This equation expresses the relationship between the electrical power measured in the electric generator and the maximum that could be ideally obtained. The pressure ratio in the expander is calculated through Eq. 2.

$$\varepsilon_{x,is} = \frac{\dot{W}_x}{\dot{m}\left(h_{x,in} - h_{x,out,is}\right)} \tag{1}$$

$$P_r = \frac{P_{x,in}}{P_{x,out}} \tag{2}$$

The electrical expander effectiveness achieved by the expander prototype in the test bench is represented in Figure 4.

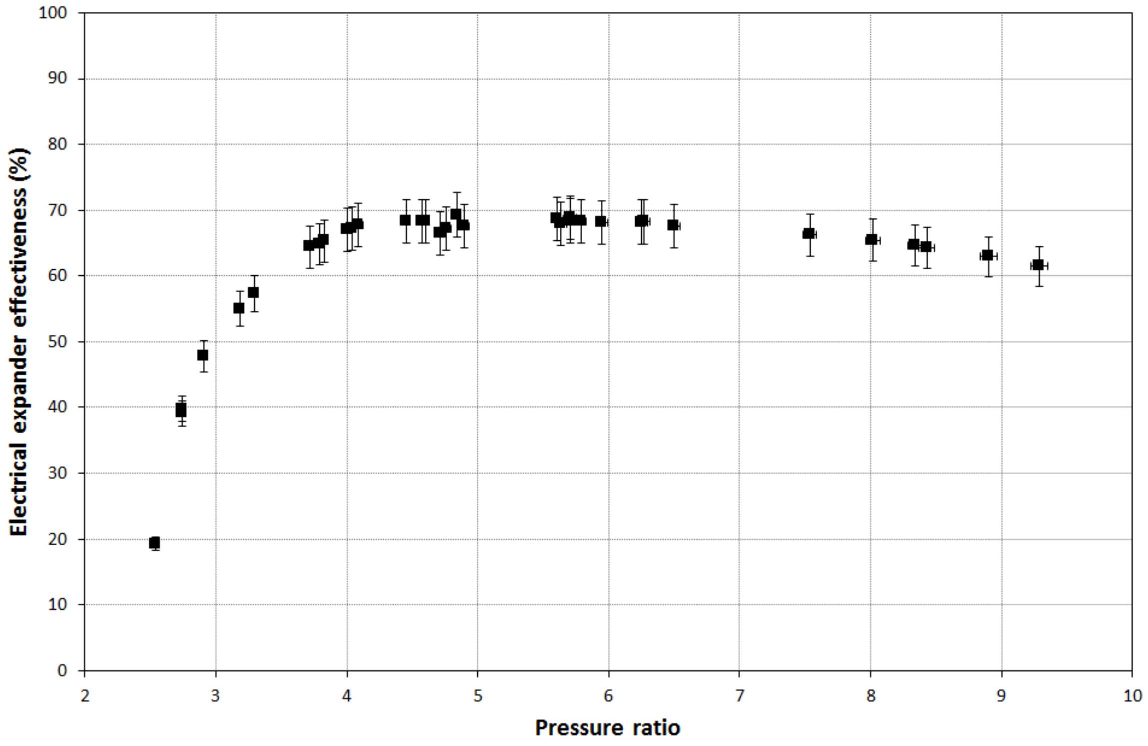


Figure 4: Electrical expander effectiveness achieved

The experimental results from the expander have been used in order to predict the expected behavior of the ORC module. The performance of the cogeneration system, producing hot water at 70ºC, is summarized in Table 3, with an uncertainty of ±15%.

Table 3: cogeneration mode performance

Heat source transfer fluid	Thermal oil
Heat source inlet temperature (ºC)	245
Heat source outlet temperature (ºC)	173.3
Heat source flow rate (m^3/h)	11.8
Heat source thermal power (kW)	480
Heat sink transfer fluid	Water
Heat sink inlet temperature (ºC)	60
Heat sink outlet temperature (ºC)	70
Heat sink flow rate (m^3/h)	34.1
Heat sink thermal power (kW)	390
Gross electrical power (kW)	70

6. CONCLUSIONS

This work presents the design process of a micro scale ORC, suitable for a Combined Cold, Heat and Power (CCHP) application that uses solar biomass supported renewable energy as heat source. The technical requirements of the equipment, working fluid selection, thermodynamic cycle configuration, design and expected performance are presented.

The technical requirements of the equipment imposed by the application are the boundary conditions that constrain the design process of the ORC system. Attending to the renewable heat source activation, it consists on a solar biomass supported heat source. The heat sink is used to produce hot water for heating or hot water to activate an adsorption chiller.

Different working fluid options have been analyzed and evaluated for their application in the current application based on the suitable fluids found in the literature. Special attention has been taken in security properties, as toxicity and flammability, thermal stability and environmental properties. HFC-245fa has been selected as the best available working fluid candidate, with low toxicity, no flammable, maximum allowable temperature below 250ºC and good expected efficiencies.

Various possible modifications to the simple ORC plant layout are analyzed and compared, in order to improve the ORC recovery performance. The possibility of working in transcritical conditions has been rejected due to the increase on the pump consumption that reduces the net efficiency of the cycle. The adoption of a recuperative heat exchanger has been selected, due to the improvement on the efficiency by reducing the thermal power required.

With the working fluid, configuration and operating conditions selected, the next step has been the selection of the components of the ORC module and their design. The expander design has been addressed and an expander prototype has been obtained. The performance of this expander prototype has been experimental characterized in the test bench constructed ad-hoc for the expander tests. Finally, the experimental results from the expander prototype have been used to obtain the expected performance of the ORC module working in cogeneration mode and producing hot water at 70ºC to activate the adsorption chiller.

NOMENCLATURE

ε	efficiency	(%)
h	specific enthalpy	(kJ/kg)
m	mass flow rate	(kg/s)
P	pressure	(bar)
T	temperature	(ºC)
W	electrical power	(kW)

Subscripts

crit	critical
in	inlet
is	isentropic
max	maximum
out	outlet
r	ratio
x	expander

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