SMALL-SCALE ORGANIC RANKINE CYCLE FOR DOMESTIC BIOMASS FUELLED COMBINED HEAT AND POWER APPLICATIONS

Joaquín Navarro-Esbrí[1], Marta Amat-Albuixech[1]*, Adrián Mota-Babiloni[1], Francisco Molés[1], Carlos Mateu-Royo[1], Manuel González[2], José Pascual Martí[2]

[1]ISTENER Research Group, Universitat Jaume I
www.istener.uji.es
Castellón de la Plana, Spain
mamat@uji.es

[2]Expander Tech S.L. (Rank),
www.rank-orc.com
La Vall d'Uixó, Castellón, Spain
info@rank-orc.com

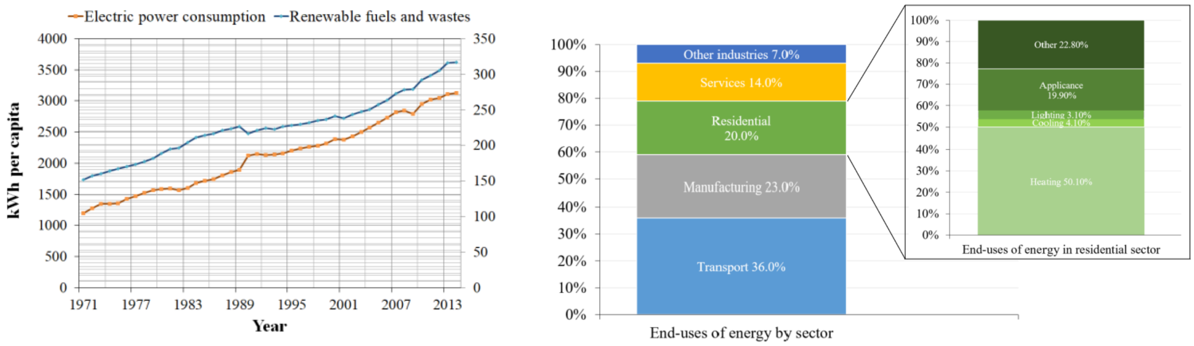
ABSTRACT

Environmental concerns have made increase the interest on energy efficiency and renewable energy sources. Domestic buildings are one of the main fields of energy consumption, mainly in the form of electricity and heating systems. Therefore, the use of Combined Heat and Power systems and renewable energy sources in domestic applications is a very interesting option to reduce fossil fuels consumption. Organic Rankine Cycle is one of the most attractive technologies in terms of low temperature and small-scale applications, producing not only electricity but also useful heat through the exploitation of the condensation thermal power. This paper presents the preliminary tests of a small-scale ORC for domestic biomass fuelled Combined Heat and Power applications using commercial biomass boilers. This system has been conceived to operate as a CHP technology, using the thermal energy provided by the condenser for domestic heating, with outlet water temperatures up to 45ºC. The main characteristics on the ORC will be presented with a basic cycle configuration and using HFC-245fa as working fluid. The system has been designed for a maximum electrical output of 1.5 kW.

1. INTRODUCTION

The significant energy consumption makes increase the need for a change that allows to conserve the environment. Although in recent years the use of renewable energy has increased (secondary axe), the consumption of energy has done so in a much more important way (primary axe), Figure 1(a) (IEA, 2018), in fact, the renewable energy represents between 9.7 % and 12.7 % of the total energy consume; and considering that most of the energy consumed comes from fossil fuels, the problem becomes increasingly important. Due to the high amount of greenhouse gas emissions, governments have created some legislations, such as the Paris Agreement (United Nations, 2015), which aims to reduce the environmental impact of our actions. Therefore, during the last years the prohibitions and restrictions have been growing, as well as the awareness towards the adoption of more environmentally friendly behaviours.

So, energy efficiency stands out as one of the mechanisms to reduce the carbon footprint (Eichhammer et al., 2009; Organisation de coopération et de développement économiques, 2014), therefore, the implementation of technologies that make it possible is becoming increasingly necessary. From the data provided by the international agency (IEA, 2018), it is seen how the energy consumption in homes has an important weight, around 20 % of total consume of which 50 % is used for heating, i.e. around the 10 % of the total consume, Figure 1 (b). Thus, the possibility of using renewable energies at the household level is increasingly being considered; and among renewable energy sources, biomass highlights due to its accessibility, which facilitates its implementation at the domestic level. Organic Rankine Cycles (ORC) are a very interesting choice in order to recover heat at relatively low temperatures, such as the provided by domestic biomass boilers. The ORC is a low-complexity power cycle with little maintenance requirements that offers a good performance by taking advantage from energy sources at low temperature (Turizo et al., 2013).



(a) (b)

Figure 1: (a) Electric power consumption and renewable fuels and wastes over the years, (b) Largest end-uses of energy by sector in 2015 (the analysed data comes from IEA countries: Australia, Austria, Canada, Czech Republic, Finland, France, Germany, Greece, Ireland, Italy, Japan, Korea, New Zealand, the Netherlands, Spain, Sweden, Switzerland, the United Kingdom and the United States).

The present work shows the commissioning results of a small-scale and low-temperature ORC unit used in a Combined Heat and Power (CHP) application, where a biomass boiler is used to provide the thermal energy required to produce electrical power at the same time that thermal heat provided by the condenser is profited in a domestic heating system. The analysis has been performed varying the activation temperature between 75 ºC and 90 ºC, and the ORC unit is in charge of heating the water flow for the heating system up to 40 ºC.

2. SETUP AND DATA VALIDATION

The experimental tests have been carried out with a commercial ORC, a micro-scale and low-temperature ORC module. This ORC module uses HFC-245fa as working fluid and has a basic architecture, i.e. its main elements are a pump, evaporator, expander and condenser, Figure 2. The ORC used for the experimental tests is designed for using commercial biomass boilers (thermal power up to 40 kW) producing electricity (1-2.5 kW) and thermal power in the form of hot water up to 50 ºC (17.5-35 kW).

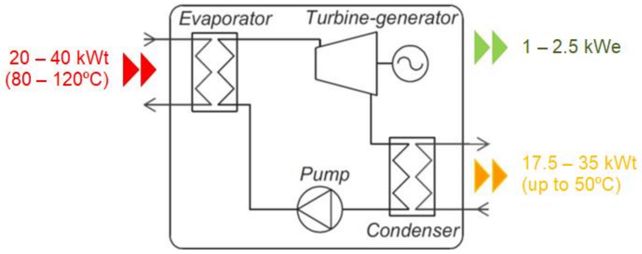


Figure 2: ORC module configuration.

The experimental tests are carried out using a thermal oil boiler varying the activation temperature between 75 ºC and 90 ºC, and maintaining the hot water production at 40 ºC using a dry-cooler to simulate the heating thermal load.

The experimental tests have been obtained using a data acquisition system, constantly monitoring the ORC module, which allows getting the necessary data to analyse the cycle behaviour, such as temperatures, pressures, flow rates, electric power, etc. Each component is measured at the inlet and outlet by K-type thermocouples (±0.5 ºC) and piezoelectric pressure gauges (±0.5 kPa). Two digital wattmeters (±1.55 %) provide the electrical power consumed by the pump and generated by the expander. The working fluid mass flow rate is obtained by a Coriolis effect mass flowmeter (±0.3 %) and, depending on the loop, the volumetric flow rate is calculated in two different ways: a Vortex flowmeter (±0.028 m3/h) has been used for the thermal oil loop and an electromagnetic flowmeter (±0.5 %) for the water loop.

These data are collected every 1 second, so in order to extract the information, some representative steady states of 300 measures (5 minutes) have been selected and averaged in order to be used as a steady-state. The RSS method has been employed to calculate the characteristic parameters uncertainty propagation. The commissioning has been studied using REFPROP 10.1 (Lemmon et al., 2018) to calculate the different parameters, and the following equations have been applied at this process (Equation 1 to Equation 5).

$$Q_{evap} = \dot{m} \cdot (h_o - h_i) \tag{1}$$

$$Q_{cond} = \dot{m} \cdot (h_i - h_o) \tag{2}$$

$$\eta_{net} = \frac{W_x - W_p}{Q_{evap}} \tag{3}$$

$$\eta_{is,x} = \frac{h_i - h_0}{h_i - h_{0,is}} \tag{4}$$

$$\eta_{ov,x} = \frac{W_x}{\dot{m} \cdot (h_i - h_{o,is})} \tag{5}$$

The presented preliminary tests show the ORC behaviour at the commissioning process for a biomass boiler with maximum temperature of 90 ºC; the tests have been developed by varying the activation temperature from 75 ºC to 90 ºC. The secondary water flow temperature at the condenser inlet is approximately 30 ºC; the ORC makes a temperature step around 10 ºC, so finally the water flow provided to the domestic heating system is at 40 ºC.

Furthermore, a thermal balance has been developed in order to validate the experimental data; Figure 3 shows the water heat rate at the condenser as function of the thermal power provided by the working fluid at the condenser. The maximal relative difference obtained taking the last one as a reference is up to ± 2.6 %, which is as an indicator of the correct running of the ORC unit, as well as its monitoring system.

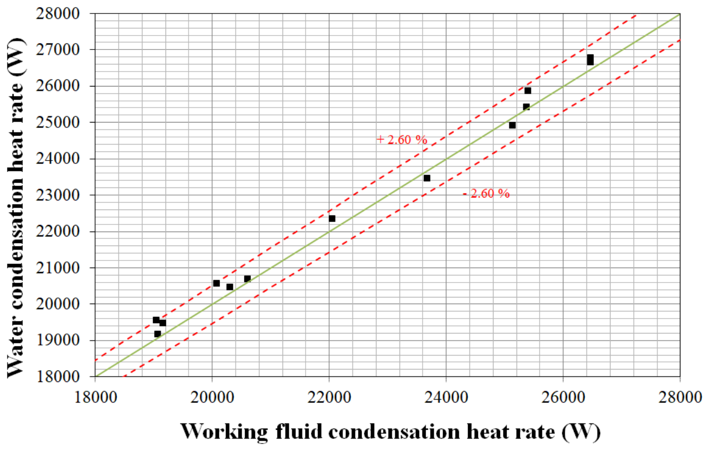


Figure 3: Thermal balance at the condenser.

In order to quantify the economic saving achieved by the implementation of this ORC module, the Equation 6 has been applied; the profit is calculated for each operating hour, and gas heating system has been taken as reference. Assuming that the ORC facility is located in Spain, some parameters based on the current market prices have been stated, Table 1. Then Equation 7 provides the payback period, where the study will be developed assuming 3000 hours of annual operating time.

$$S = Q_{evap} \cdot (C_e \cdot \frac{\eta_{net}}{100} + C_{gas} \cdot \frac{\eta_{th}}{\eta_{gas}} - C_{bio} \cdot \frac{100}{\eta_{bio}}) \qquad (6)$$

$$Payback = \frac{Investment}{S_{annual}} \qquad (7)$$

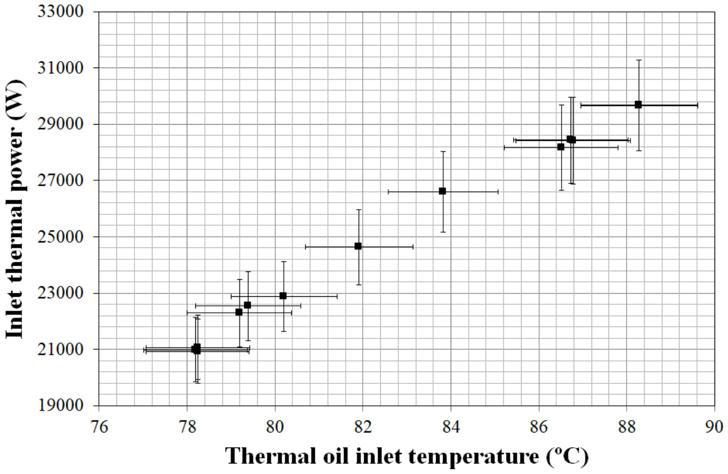
Table 1: Required parameters to calculate the economic saving.

Electrical price	0.2383 €/kWh
Biomass price	0.0376 €/kWh + VAT
Boiler efficiency	91 %
Gas heating installation efficiency	90 %
Contracted fee for the gas heating installation	0.05076 €/kWh

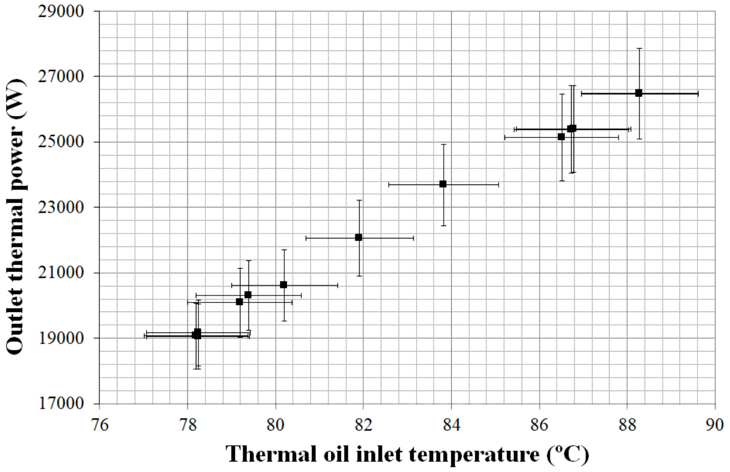
3. EXPERIMENTAL RESULTS

This work shows the behaviour of an ORC unit working as a CHP system, taking the heat provided by a thermal oil boiler as heat source and using the heat provided by the condenser to increase the temperature of a water flow, which will be used for domestic heating. So, following results show the behaviour of a real ORC unit in its start-up phase; this system provide water for domestic heating at 40 ºC from activation temperatures provided by the biomass boiler between 75 ºC and 90 ºC.

Figure 4(a) shows the thermal power provided to the ORC. The heat rate at the evaporator increases by raising the activation temperature, adding nearly 1 kW each 1 ºC growth. Practically, the great part of the power supplied by the heat source is used in the heating system, Figure 4(b), since the cycle has a thermal efficiency around 90 %.



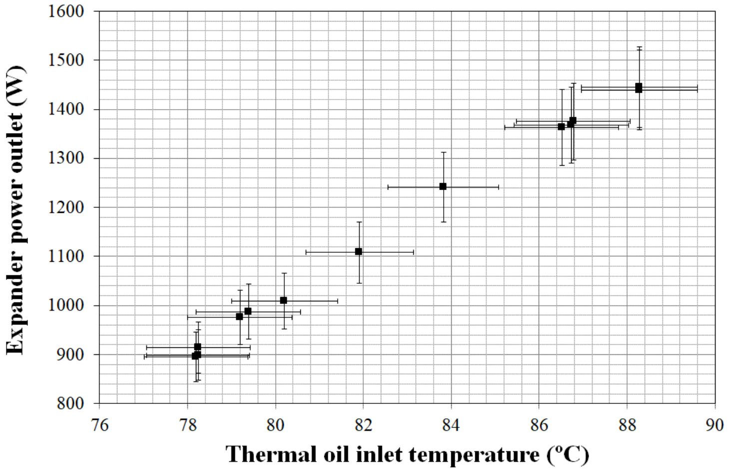
(a)



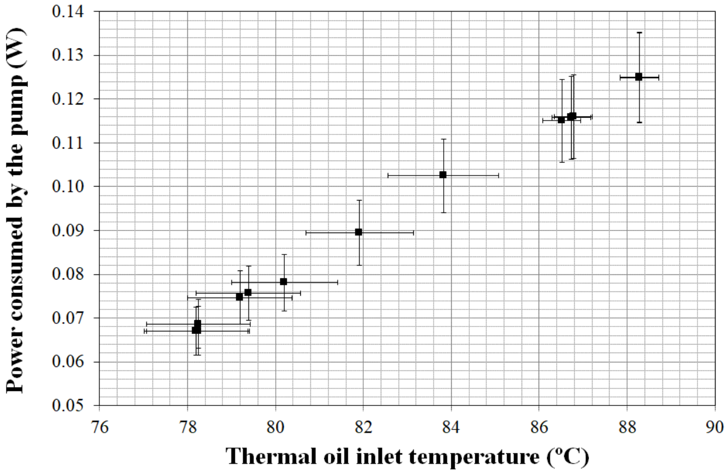
(b)

Figure 4: (a) Inlet thermal power, **(b)** Outlet thermal power varying the thermal oil inlet temperature.

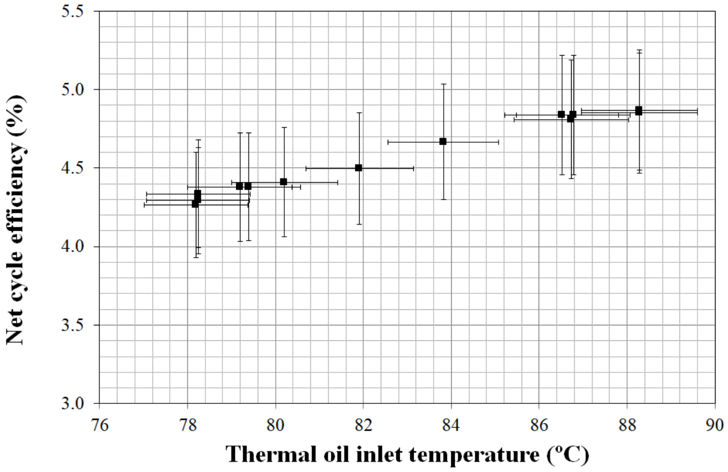
Figure 5(a) shows the evolution of the power generated by the expander as a function of the activation temperature. This image shows how, as expected, the higher the temperature of the heat source is, the greater the power that the expander is able to generate is. This is because the superheat has been left at a constant value, thus evaporation temperature increases so the enthalpy difference is higher. Although this activation temperature growth causes higher pump consumption, nevertheless, the second one is much lower compared to the power produced by the expander, Figure 5(b). While the expander power output is between 0.90 kW and 1.45 kW, the pump only consumes between 0.07 W and 0.12 W. So finally, Figure 5(c) shows the net efficiency of the cycle, which reaches values between 4.27 % and 4.87 % depending on the activation temperature. It must be considered that, even though the net cycle efficiency is low, a good performance of the cycle is achieved. There is not only the electrical production which must be considered; the ORC commissioned unit has been designed to work as a CHP system, therefore all the heat provided by the condenser is being used for the heating system instead to be wasted.



(a)



(b)



(c)

Figure 5: (a) Expander power outlet, **(b)** Power consumed by the pump, **(c)** Net cycle efficiency varying the thermal oil inlet temperature.

To sum up, Figure 6 shows the economic saving provided by the ORC facility. Considering the ORC as a gas heating system replacement in a Spanish household, the profit is between 0.24 €/h and 0.35 €/h. Figure 6(a) provides an idea of the economic saving that the domestic implementation of this technology as a CHP system entail. Nevertheless, the economic saving can change strongly with the location of the facility, since the price per electric kW changes depending on the country; so, the implementation of this technology in those places where the electricity and gas have a higher price will be more profitable. Finally, in order to assist to judge the market prospects, Figure 6(b) shows the required investment of the implementation of the ORC facility for 3000 hours of annual operation, where three payback periods have been raised.

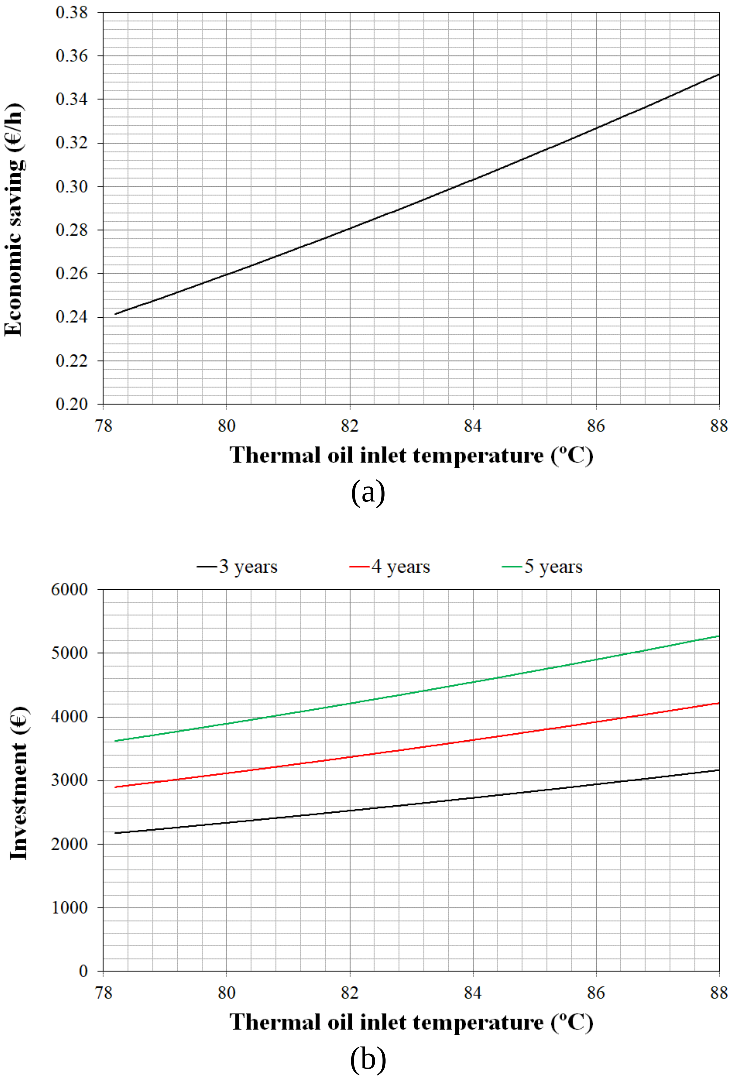


Figure 6: (a) Economic saving per operating hour varying the thermal oil inlet temperature, **(b)** Investment for different payback periods.

4. CONCLUSIONS

During the present work the start-up of a small-scale and low-temperature ORC unit has been carried out. This ORC module works as a CHP system, prepared for using a biomass boiler as heat source and providing heat to a water flow, which will be used for domestic heating. The preliminary commissioning tests have been carried out using a thermal oil boiler and varying the maximum temperature up to 90 ºC (according to the biomass boiler that is going to be finally used). As expected, better results are obtained for the higher temperature of the heat source. In this way, producing heat water at 40 ºC, the ORC module has a net cycle efficiency up to 5 % for a 90 ºC heat source inlet temperature, with a the thermal efficiency about 90 %. Finally, in terms of electrical power production, it ranges from 0.90 kW to 1.45 kW using between 20 kWt and 30 kWt as activation thermal power. It has to be noted that higher thermal and electrical powers, and net cycle efficiencies, would be obtained with higher heat source inlet temperatures (up to 120 ºC).

NOMENCLATURE

C	cost	(€)
h	specific enthalpy	(kJ/kg)

m	mass flow rate	(kg/s)
Q	heat rate	(kW)
S	economic saving	(€/h)
W	electrical power	(kW)

Greek symbols

η	efficiency	(-)

Subscripts

bio	biomass
cond	condensation
e	electricity
evap	evaporation
i	inlet
is	isentropic
net	net
o	outlet
ov	overall
p	pump
th	thermal
x	expander

Acronyms

CHP	Combined Heat and Power
ORC	Organic Rankine Cycle

REFERENCES

Eichhammer, W., Fleiter, T., Schlomann, B., Faberi, S., Fioretto, M., Piccioni, N., Lechtenböhmer, S., Schüring, A., Resch, G., 2009. Study on the energy savings potentials in EU member states, candidate countries and EEA countries. Final report. Karlsruhe.

IEA, 2018. International Energy Agency [WWW Document]. URL https://www.iea.org/statistics/?country=WORLD&year=2016&category=Key indicators&indicator=TPESbySource&mode=chart&categoryBrowse=false&dataTable=BALANCES&showDataTable=false (accessed 11.26.18).

Lemmon, E.W., Bell, I.H., Huber, M.L., McLinden, M.O., 2018. NIST Standard Reference Database 23, DLL number version 10.0.

Organisation de coopération et de développement économiques, 2014. Energy Efficiency Indicators: Fundamentals on Statistics, OECD.

Turizo, J.C., Fontalvo, A., Amador, G., González, A., Vásquez, R., Bula, A., 2013. Análisis y optimización de un ciclo Rankine orgánico basado en energía solar empelando diferentes fluidos de trabajo, in: Congreso Iberoamericano de Aire Acondicionado y Refrigeración - CIAR 2013. Cartagena - Colombia.

United Nations, 2015. The Paris Agreement (English version) [WWW Document]. URL https://unfccc.int/sites/default/files/english_paris_agreement.pdf

ACKNOWLEDGEMENT

The authors want to acknowledge the Regional Government for the financial support under grant FEDEGENT/2018/002. Furthermore, the authors acknowledge the University Jaume I of Spain for the financial support under project UJI-B2018-24 and project GACUJI/2019/24. Also acknowledge the Ministerio de Ciencia, Innovación y Universidades and the Spanish government for the financial support under project RTC-2017-6511-3. Carlos Mateu-Royo acknowledges the funding received through the PhD grant PREDOC/2017/41. Finally, we want to acknowledge Expander Tech S.L. for the commercial Rank® MICRO used to develop the experimental tests.