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Development and Experimental Characterization of a Small scale Solar Powered Organic Rankine Cycle (ORC).

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Abstract

Solar thermal power plants have been widely studied in recent years as solar energy is clean, affordable and largely available. The possibility of converting solar thermal energy into electricity with small scale (lower than 10 kWe) Organic Rankine Cycle (ORC) plants operating at low temperature (lower than 130°C), seems today a viable option. In this paper, the design and development of a prototypal small scale ORC plant (< 10 kWe) is presented. The ORC, equipped with a scroll expander and installed in Florence, Italy, is powered by parabolic trough solar collectors (PTC) with collector surface area of 100 m^2. In the first part of the paper the experimental data collected during the lab tests are presented. Then, the data collected during the field test are presented and discussed. A gross electrical efficiency up to 8% has been achieved. The value of net efficiency is dependent on the power absorbed by the auxiliary components that have not been optimized yet.

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Keywords: Solar-ORC; experimental analyses; prototype; scroll expander; PTC.

1. Introduction

Distributed co-generation using solar energy is gaining significant interest [1-2]. One of the technologies largely studied in the recent years is the Organic Rankine Cycle (ORC) [3]. ORC systems are generally suitable for the

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recovery of low grade heat with low pressure levels of the cycle operating fluid; this is a major advantage of the system in terms of safety, simplicity in construction, availability of components and system management. Flat plate solar collectors require a lower capital investment, compared to concentrating systems, such as parabolic trough [4] though the latter ensure a higher total amount of produced energy throughout the panel operating life [5], especially if equipped with sun tracking systems [6]. At system level, the coupling between a solar system and an ORC unit have largely been studied by several authors [7–10]. Tchanche *et al.* [11] demonstrated the benefits achieved in terms of systems' energy and thermal efficiencies by coupling a solar ORC to a desalination unit. For their investigation, a basic architecture with a regenerative cycle was considered; three expansion devices and three working fluids were analyzed. Wang *et al.* [12] built and tested an experimental small scale low temperature solar Rankine Cycle system featuring a direct evaporation of the working fluid R245fa. Two typologies of collectors were chosen for their installation: the flat plate and the evacuated tube types. The average solar to electric conversion efficiencies without considering the power consumed by the auxiliaries were 3.2% and 4.2% respectively. Successively Wang [13] presented a very small ORC system equipped with flat plate collectors with the aim of comparing different working fluids, both pure substances and mixtures. The experimental tests confirmed the potentiality of zeotropic mixtures of achieving good performance in ORC applications due to their typical non isothermal phase changes and revealed the importance of the optimization of the working fluid flow rate. A recent study by Freeman *et al.* [14] is also available on the performance and economic analyses of a small scale Combined Solar Heat and Power (CSHP) system based on an ORC. Chambers *et al.* [15] described a pilot scale parabolic trough solar thermal power unit coupled with an ORC where they presented a feasibility study of cost-effective commercial scale solar thermal power production in Louisiana. In a conference paper on Solar Energy Technologies, Canada *et al.* [16] described a 1MWe parabolic trough solar plant installed in Arizona which demonstrated the potentials of the ORC technology for large scale centralized power generation. Jing *et al.* [17] presented a simulation model of a solar ORC installation with dedicated sub-models for solar radiation, collectors behavior, and thermodynamic cycle performance. The model used for a global optimization of the system revealed that the best configuration varies according to the geographical location, since the intensity and the distribution of solar radiation are the most influencing factors on the system performance. Kane *et al.* [18] designed, built and optimized a mini-hybrid solar power system suitable for installation in remote areas of developing countries, the main components of the plant are a 100 m^2 field of solar concentrators, two scroll expanders in the ORC unit and a diesel engine, the purpose of the latter being to guarantee a minimum level of both power and heat availability at night or during cloudy periods.

Nomenclature

CSHP	Combined Solar Heat and Power		
HVAC	Heating, Ventilation and Air Conditioning	ICE	Internal Comb. Engine
ORC	Organic Rankine Cycle	HMDSO	Hexamethyldisiloxane
PTC	Parabolic Trough Collectors	RORC	Regenerative ORC
P_exp	Expander power	Q_coll	Collector thermal power
T_out_coll	Collector outlet temperature	p_evap	Evaporator pressure
WHR	Waste Heat Recovery	T_in_ORC	ORC inlet temperature
C_1	1° order loss coefficient	T_evap	Evaporation temperature
η_{is}	expander isentropic efficiency	C_2	2° order loss coefficient
η_system	System overall efficiency	η_0	Optical efficiency

The field test confirmed the possibility to achieve acceptable performances with the prototype, even at partial loads, a fundamental feature for a system designed to operate in stand-alone mode. In terms of ORC system architecture, Lecompte [19] suggests in his work some solutions like the use of a recuperator, a regenerative ORC, an Organic Flash Cycle, a Transcritical Cycle and a Trilateral Cycle. Giving the importance of working fluids in micro-ORC's, Bao *et al.* [20], for example, discuss the selection criteria. Other selection criteria studies and comparisons for both pure and fluid mixtures can be found in [22–24]. Effects of control strategy and part load operation on ORC performance are analysed in [25-26]. This paper presents the development of an ORC prototype coupled to a Parabolic Trough solar collector system. The analyses involves laboratory experiments of the ORC prototype using electrical resistances to simulate the heat source as well as the field test performed on the combined Solar-ORC installation at Florence, Italy. The field test results confirm the feasibility of the combined solar ORC system and the potential profits obtainable with such a combination in terms of electric and thermal generation.

2. Description of the system

The solar-ORC system presented in this work is described considering two subsystems: ORC and solar collectors. The ORC prototype is designed for low grade waste heat recovery with a nominal power output of 2kWe. The working fluid used in the power cycle is the R245fa, following the selection criteria discussed in [26]. The prototype was designed according to the architecture of a regenerative ORC (RORC) with an internal heat recuperator to improve the overall cycle efficiency.

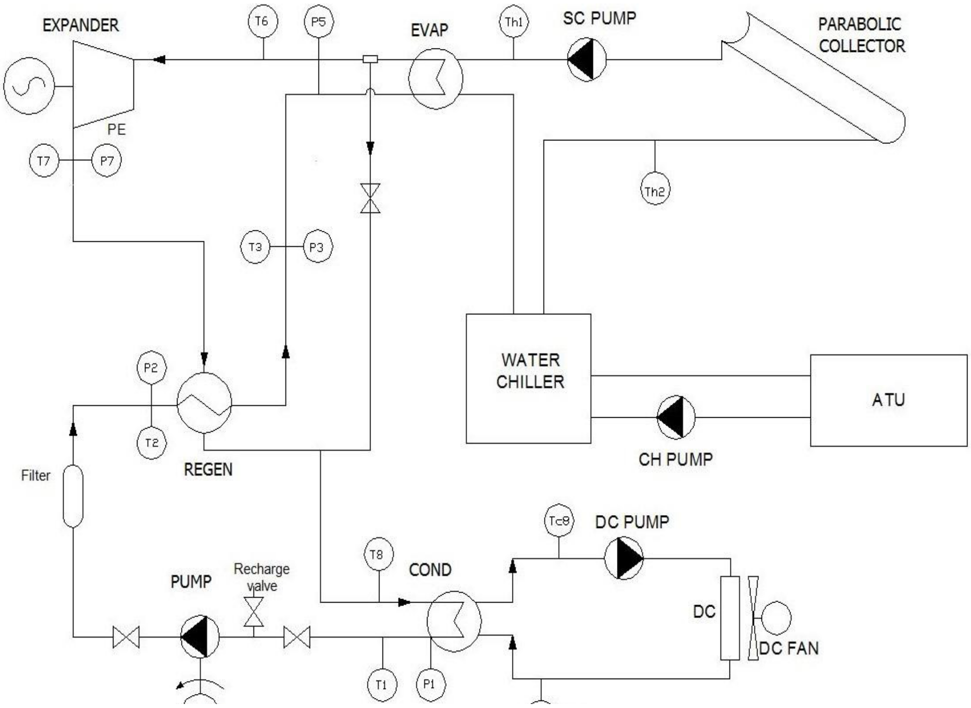

Fig 1. Schematics of the experimental solar thermal system

The main components of the cycle include the following elements; a) the expander: a positive displacement scroll type with isentropic efficiency between 65-70%, b) an inverter driven feed pump: a positive displacement gear type generally employed in operations involving light oils and other fluids with low viscosity, c) the heat exchangers: the evaporator, the condenser and the regenerator; all three elements are of the same type (plate heat exchangers). An air dry cooling unit for heat removal is also integrated in the system with the cooling water running in a closed loop by means of a water pump. The simplified layout of the system is shown in Fig 1.

The ORC prototype has been installed in Florence (Italy) in an existing solar cooling facility, developed by the University of Florence, composed principally of two different types of collector strings for a total of 98m^2. Both collector types are parabolic trough collectors (PTC). The first collector type is a one axis tracking trough PTC1800 produced by Solitem [27] with a tracking precision of 0.1°, the second type is a prototype panels developed by FeroTech [28].

Table 1 Technical data of the facility solar collectors

Type	model	n° of panels/size	η_0 [-]	C_1 [W/m²K]	C_2 [W/m²K²]	*T range* [°]
1	Solitem PTC1800	6 [5.02x1.8 m]	0.6833	0	0.0033	100-250
2	Fero PTC1600	5 [5.4x1.54 m]	n/a	n/a	n/a	100-250

2.1. Preliminary laboratory tests

The laboratory at the University of Trieste is equipped with an ORC test bench connected to a set of electric resistances used to simulate the heat source that, in the specific application, will be the solar field. The heat transfer medium employed within the electric resistances is a treated vegetable oil. The thermal fluid runs in a closed loop made of: a storage tank, two electric resistances with a thermal capacity of 41 kW each in a parallel arrangement, a process pump for the circulation of the oil through the resistances and a second pump used to drive the hot oil from the storage tank to the ORC evaporator, where the heat exchange with the working fluid of the vapor cycle (R245fa) takes place. Heat removal from the ORC unit of the test bench was obtained by a cooling water system in an open loop. In order to dissipate the electricity produced by the prototype, an electric load is electrically connected to the expander. The data acquisition system is based on K-type thermocouples, pressure transducers and a Coriolis (Kobold, model TME) mass flow meter.

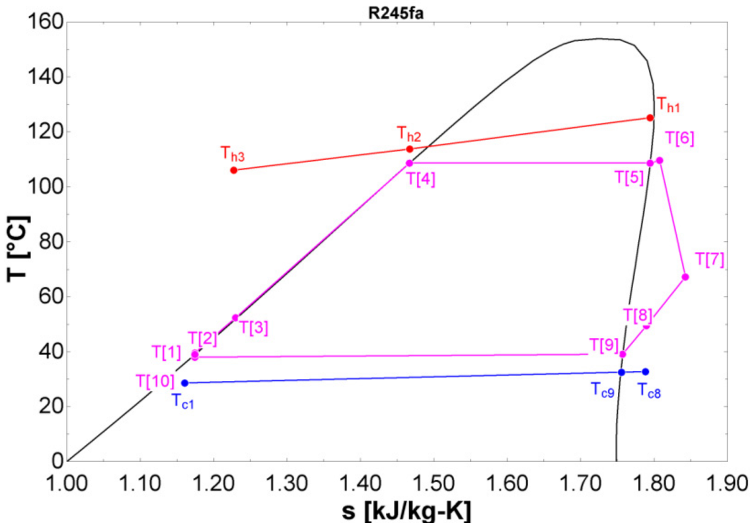

Fig 2 T-s diagram of the thermodynamic cycle for R245fa

The data collected during the laboratory work include: the thermal oil and fluid mass flow rates, the electric power generated by the expander, temperatures and pressures of the fluid measured along the circuit. The electric power absorbed by the auxiliaries (the ORC feed pump, inverter and data acquisition system) was measured using a power meter. The thermodynamic cycle diagram for the working fluid employed in the system can be seen in Fig 1. The ORC test bench has been utilized to characterize the performance of the scroll expander used in the prototype. A specific test bench for pump testing is also available and it has been used to assess the performance of the pump used in the ORC prototype with fluid of different viscosity. The ORC prototype, later installed in Florence, has been tested in the lab using the electrical heater. Some of the experimental data presented are not complete as some information are protected by confidentiality agreements with components suppliers and project partners.

The expander is adapted from a scroll compressor used in air conditioning systems. The scroll is a positive displacement machine essentially formed by two identical spiral-shaped wraps fixed on back plates. One wrap has a hole in the back plate and is held fixed, while the other can orbit. If the machine is used as an expander, the working fluid enters the central chamber through the fixed back plate hole, then it moves towards the external endings of the wraps and exits. The drawbacks of this kind of solution are mainly two: the low fixed volumetric expansion ratio and the small displacement volume, that are not always well-suited for the requirements of power producing ORCycles.

A systematic collection of data describing the actual behavior of compressors derived scroll expanders has been acquired on the test rig. In particular, the values of expansion ratio, net produced power and isentropic efficiency have been measured on an expander with a displacement volume of 9.1 cm^3, using R245fa as working fluid. This test has shown that the maximum overall isentropic efficiency $\eta_{is,}$ (about 62%) is achieved for an expansion ratio of the scroll machine equal to about four. Such a value of efficiency can also be found in literature, as in [4], although higher values (up to 68-70%) have been reported in [3]. In many cases, however, the value of efficiency measured in actual operating conditions is too small to achieve a good performance of the power cycle and multiple expanders systems can be considered [33]. In Fig 3, where the expander efficiency is shown as a function of the expansion ratio, it is possible to see that when high expansion ratios are imposed, the expander efficiency is much lower than its maximum value. It is also possible to see in Fig 4 the trend in the expander electric power generated as a function of the expansion ratio.

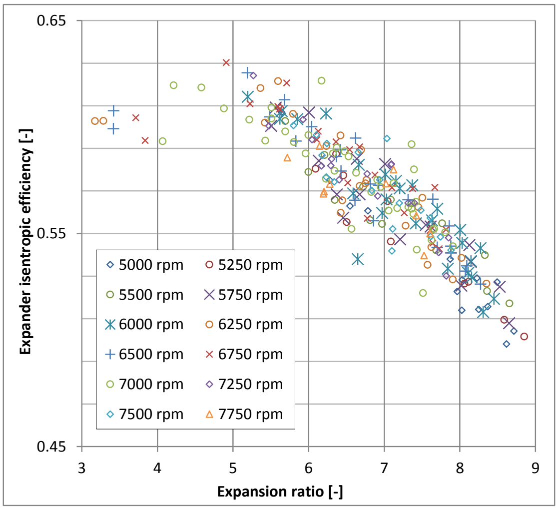

Fig 3 Expander isoentropic efficiency vs. the expansion ratio at various rotational speeds, with R245fa as working fluid.

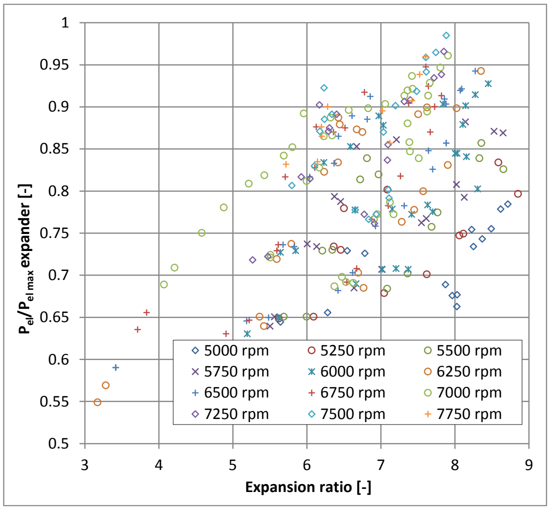

Fig 4 Expander electric power (dimensionless) vs. the expansion ratio at various rotational speeds, with R245fa as working fluid.

In the experimental tests the temperature of the heat source has been regarded to vary in the range 90°-150°C. This range can be typical for geothermal applications and medium temperature solar thermal collectors. In particular, the latter applications can be of interest if a solar cooling system is included as well. The experimental data have been used to develop a process simulation model [30-31] to better understand the sensibility of the cycle to the operating conditions.

Regards the gear pump, a preliminary test was carried out separately on a pump test bench to investigate the general performance of the component before mounting it on the prototype. The test was initially done with gasoil then with R245fa. Results of the test are shown in Fig 5, where the fluid flow rate is given as a function of pressure increase. Data show, as expected, that increasing the delivery pressure the flow rate is reduced with R245fa, as its viscosity is lower.

Once the design phase was completed, the ORC prototype was built and tested in the laboratory. The tests were carried out at different expander speeds (3000-8000 rpm) with the temperature of the heat source ranging from 90-130°C typical of solar thermal systems. A selection of the results is presented in Table 2

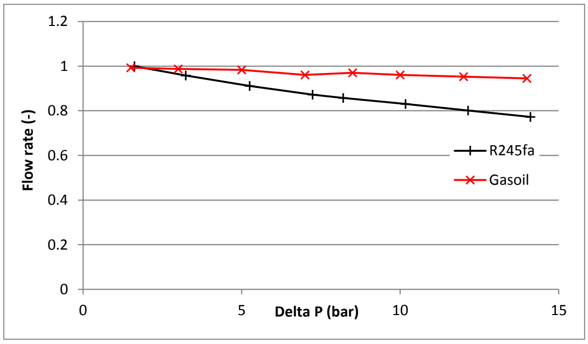

Fig 5 Gear pump characteristics with gasoil and R245fa. Flow rate referred to max flow rate with Gasoil

Table 2 Selection of the results during the lab test of the prototype

ORC-R245fa circuit			Thermal oil circuit	
P_exp [W]	T_out_evap [°C]	Exp. Speed [rpm]	Flow rat e[kg/h]	T_in_eva [°C]
905	100.9	6000	700	106.7
870	99.9	5000	700	95.2

2.2. Field tests

The ORC prototype was then installed in Florence coupled to an existing solar field designed for solar cooling as well. The integration of the prototype was obtained by modifying the piping of the existing circuit. The first field tests were carried out in November 2015 and the preliminary results obtained are discussed in this section. Unfortunately, solar radiation was very low and it was not possible to collect experimental data covering all the operation range of the ORC prototype. Two sets were carried out: in the first one a set of data was registered at a constant expander speed (6000 rpm) and collector water flow rate of 4200 kg/h. The second was carried out at constant collector water flow rate (1800kg/h) at different expander speeds within the range (4000-6000 rpm). In both cases the R245fa flow rate was kept constant and the peak value registered for the solar radiation was 590 W/m^2 at the ambient temperatures of 19°C. The plant is visible in Fig 6: on the left are shown the solar collectors while on the right there are the ORC prototype and the dry cooler. A selection of the collected data is shown in Table 3. The peak ORC power was 670 W. This power output has been obtained with a solar radiation of 590 W/m^2 and a collector outlet temperature of 100.4°C, hot water supplied at ORC evaporator inlet at 88.1°C with corresponding ORC fluid temperature of 82.5°C at the evaporator outlet and a condensation temperature of 32.2°C. The data show that the electric power output is low but very low is the evaporation temperature as well. Therefore, overall, the result seems to be promising.

Table 3 Field test preliminary results

ORC-R245fa circuit			Solar collectors circuit				
P_exp [W]	T_evap [°C]	Exp. speed [rpm]	Flow rate [kg/h]	T_out_coll [°C]	T_in_ORC [°C]	Q_coll [W]	Radiation [W/m^2]
670	82.5	6000	4200	100.4	88.1	8100	590
280	76.9	6000	1800	95.2	82.5	7700	490
400	75.4	5000	1800	94.1	80.7	9600	497
434	74.7	4500	1800	91.3	79.8	6100	532
395	72.7	4000	1800	90.4	77.8	8100	508

Moreover, a significant thermal loss has been measured from the solar collector outlet to the ORC evaporator inlet (more than 10°C over a pipe length of about 15m). This loss can be reduced by adopting an appropriate insulation and, thus, improving system efficiency.

Fig 6 The solar powered ORC. Left: the collectors; right: the ORC prototype and the dry cooler

3. Conclusions

An ORC prototype has been built, coupled with a system of solar collectors and tested for electricity production. A scroll expander has been chosen for the system that runs with R245fa as working fluid. The ORC components and ORC prototype have been characterized in lab tests. In particular, as expected, the scroll expander shows good efficiency at the design expansion ratio while performance can be poor in off-design conditions. During the field tests, an electric power output of 670W has been achieved with a low solar radiation (590 W/m^2) and significant thermal losses in hot water circuit. Therefore, it is expected that with higher solar radiation and improved thermal insulation, performance can be far better. Further field experiments have been arranged to be performed this summer 2016 and the data collected will be used to assess the potential of this technology.

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