ORC CONVERSION OF SOLAR HEAT TO ELECTRICITY AND LOW TEMPERATURE HEAT FOR DOMESTIC USE

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ABSTRACT

The following article describes a novel Organic Rankine Cycle system developed for the cogeneration of electricity and domestic hot water from solar heat. The present system is being tested in real conditions. The experience capitalized with the first runs is detailed, as well as the improvement that are consequently planned on the prototype. In particular, the working fluid choice is adapted based on pressure levels and safety considerations. The upgraded prototype is currently being built, for a test campaign during the summer.

1. INTRODUCTION

In order to tackle the challenges of energy sustainability, affordability and dependency, European Commission has launched an ambitious development program, Horizon 2020. It consists in a set of actions aiming at reducing the emissions of greenhouse gas by 20%, bringing to 20% the share of renewable energies in EU consumption and improving energy efficiency by 20%. It is in this context that the Innova MicroSolar project was born. This project consists in developing an innovative cogeneration system to produce domestic hot water and electricity to supply a small residential or professional building. The concept of Innova MicroSolar is based on three key components developed specially for this application:

- a novel flat Fresnel mirror solar concentrating collector, which aims at providing an affordable source of concentrated solar power
- a Thermal Energy Storage (TES) composed of Phase Change Material (PCM) and reversible heat pipes for the intermittent storage of heat with high efficiency
- an Organic Rankine Cycle (ORC) for the flexible production of electricity and hot water following the household needs

The target is for the whole system to supply a yearly 60% of the building energy requirements, with an objective of 18 kW of low grade heat and 2 kW of electricity for demonstration.

Solar ORC combined with TES is a promising path for decentralized and sustainable cogeneration. Medium temperature heat from a solar field is used as the heat source of the ORC, while the cold source is the heat consumption for water heating. The temperature levels at both constrain the thermodynamic cycle that leads to electricity production. Compared to combined solar thermal and photovoltaic approach, the S-ORC offers a viable alternative based on (detailed analysis can be found in [1]):

- A potentially lower installation cost, the most cost intensive part being the expander.

- A greater production flexibility. The amount of electricity and heat produced can be adapted to the household needs along the day.
- A relatively cheaper energy storage for enhanced adaptability to the daily and day-to-day consumption profile and/or solar power availability.

As a general statement, since early 2000, small scale and medium- to low-temperature ORC are attracting attention due to their large range of application [2], [3]. In particular, "solar energy" is among the most common keyword in this period [4]. In addition to the design or choice of key components/architectures (such as the expander [5] or the working fluid [6], [7]), solar applications require a precise accounting of the system's use and integration. Indeed, the techno-economic viability of the project is highly dependent on the heat consumption (in most architecture corresponding to the cold source), and even more on the location (i.e. the hot and cold sources through the climate).

Examples of performance assessments in UK[8], Lesotho[9], Cyprus[8] are reported in the literature, showing that for each of these various climates an adapted system can be designed. Finally, the complete system has to be able to adapt to the variations of the sources, and thus experimental feedback has great value. In this regards, experiments have been or are under progress in US[10] and Italy[11].

Based on the available literature and the experience of the partners, an ORC system was designed for an experimental test in Spain. Compared to existing S-ORC system, it was chosen to operate at higher temperature (in the range 180-200°C compared to below 150°C) for higher efficiency, with an adapted electricity output of up to 2kW and a temperature of cold source at about 60°C for domestic water production.. The aim is to cover efficiently most of a household energy needs (electricity and heat). Among the different technical choices made, the expander selected is an axial single-stage turboexpander developed for the project, and Novec649 as working fluid [12]. The present paper relates the first experimental test realized at the demonstration site and further enhancement that will be made on the prototype. The literature on the optimization of both heat and electricity production with small scale S-ORC is still scarce, which can make these results of interest for other groups.

2. RESULTS OF THE EXPERIMENTAL CAMPAIGN

A first experimental campaign was conducted at ENOGIA facilities. The hot source was composed of an industrial oil heater and a closed oil loop with a circulator. The cold source was composed of a dry-cooler, a water closed loop and a circulator, with variable speed for both fan dry-cooler and pump to account for the variable load expected in the final setup. The main results of the first experimental campaign were developed in [12]. This preliminary campaign allowed the fine tuning of the regulation, and to detect problematic points.

A second experimental campaign was then scheduled on the demonstration site to demonstrate the the machine performance in real conditions. The overall layout of the system is presented in Figure 1, and the design point in Table 1. At the time of the redaction of this article, only partial operation was performed. An exemplary result is shown in Figure 2. As can be seen, the temperature of the working fluid at the inlet of the turbine is too low compared to the design point (targeted temperature of 180°C) due to a too low solar irradiation. Logically, the pressure ratio of 8 is not reached (maximum pressure ratio around 4.5), and the electrical output much lower (Figure 3). Nevertheless, lessons can be extracted from these partial results.

Indeed, the pressure ratio is too low for the level of temperature at the turbine inlet. The main possible reasons can be:

- An insufficient cold source power. This possibility is investigated by checking the outlet of the heat exchanger on the water side. Its value is increasing when it should be closer to 70-75°C. Even though not problematic at this hot source temperature, the cold source regulation will have to be closely investigated for higher temperature runs.

- A low isentropic efficiency of the turbine. The measurements of the preliminary test campaign have discarded this possibility.

- The presence of a non-condensable fraction in the working fluid, such as air. This lead seems the most likely. A careful procedure was carried out for filling the circuit (including the freezing of the working fluid and extended vacuuming of the circuitry) to extract all the air possible, and the temperature of the fluid was maintained well below its decomposition point with no effect. A possible cause has been hinted to be linked to the condensation pressure at ambient temperature of the Novec649, which is below atmospheric pressure. This means that when not under operation, the whole circuitry has a pressure below atmosphere (0.3 atm at 20°C). This is an additional strain on it and a possible source of air leakage into it. This situation will have to be taken into account for the next developments on the system.

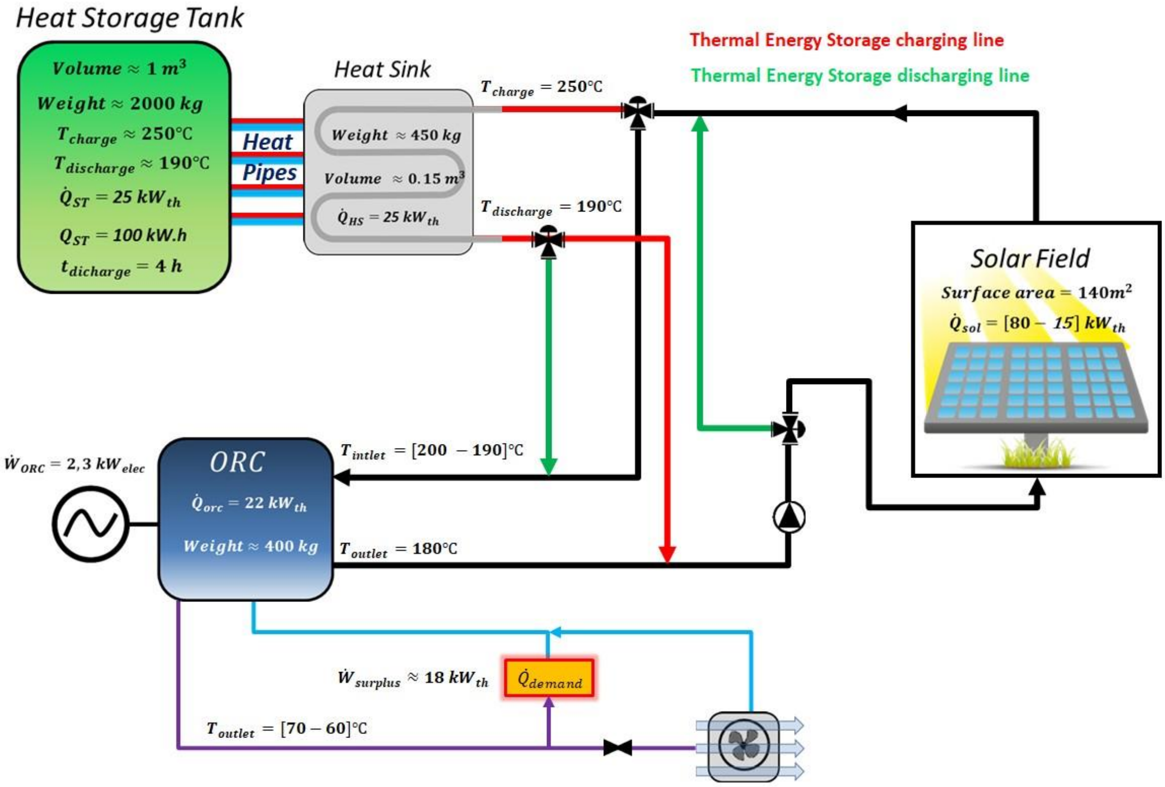

Figure 1. S-ORC system architecture

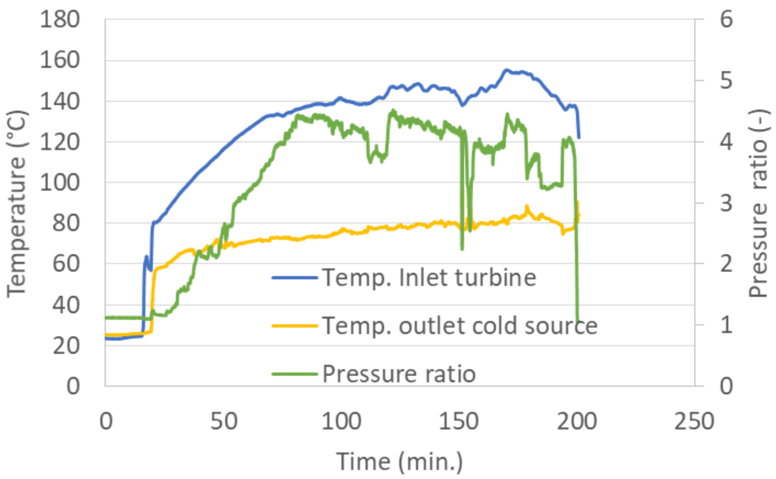

Figure 2. Temperature and pressure ratio obtained during on-site tests

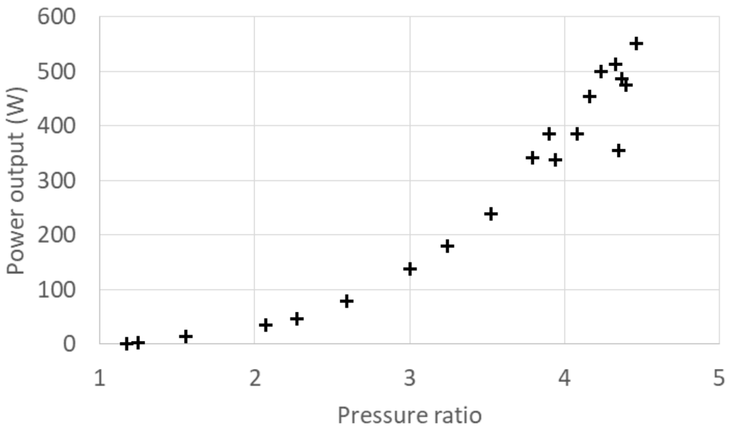

Figure 3. Electrical power produced as a function of the measured pressure ratio

3. FURTHER DEVELOPMENTS OF THE PROTOTYPE

3.1 Fluid choice

The choice of organic fluid has a deep impact not only on the thermodynamic sizing of the machine, but on its operability too. The three candidates studied at the beginning of the project are shown in the Table 1. The first has been Novec 649 because of its environmental benignity and safe operation, at the cost of the thermodynamic efficiency. As can be seen, the temperature targeted at the outlet of the evaporator is above the boiling and critical temperatures, a domain where information on the fluid behavior is scarce.
It was decided thus to adapt the fluid to the higher temperature observed, as overheating is in any case not beneficial to the system efficiency. Additionally, a higher condensing pressure at ambient temperature is desired to reduce the strain on circuitry when not under operation. Among the two remaining candidates, Cyclopentane has the best efficiency and environmental benignity, but is much more flammable and toxic. The latter argument finally oriented the choice toward r365mfc.

Physical parameter	Novec 649	Cyclopentane	R365mfc
Boiling temperature (°C)	165	188	180
Critical temperature (°C)	168	239	187
Boiling Pressure (Bar)	17,5	22,11	29,08
Superheating (°C)	5	5	5
Condensing temperature (°C)	73	73	73
Condensing pressure (Bar)	2,18	2,1	2,90
Subcooling (°C)	1	3	3
Pressure Ratio	8,02	10,52	10
Mass flow (Kg/s)	0,22	0,05	0,1
Power production (kW)	2,39	2,99	2,73
η_{cycle} (%)	10,85	13,62	12,4
Global Warming Potential	1	11	1110
Ozone Depletion Potential	0	0	0
Atmospheric Lifetime (year)	0.014	0.008	8.6
Flammability/Toxicity	No/Low	High/High	Yes in vapor phase

Table 1: Thermodynamic properties of the potential organic fluids at the sizing point

3.2 Overall thermodynamic cycle

As a result of the new design point, the new thermodynamic cycle is presented in Figure 4, the emphasisi being put on the thermal power and temperature levels. A boiling temperature of 175°C is selected, with a 5°C superheating at the heat exchanger output. The fluid is then pre-cooled in the regenerator, and then condensates at 75°C. The liquid is pumped through the regenerator where it is pre-heated.

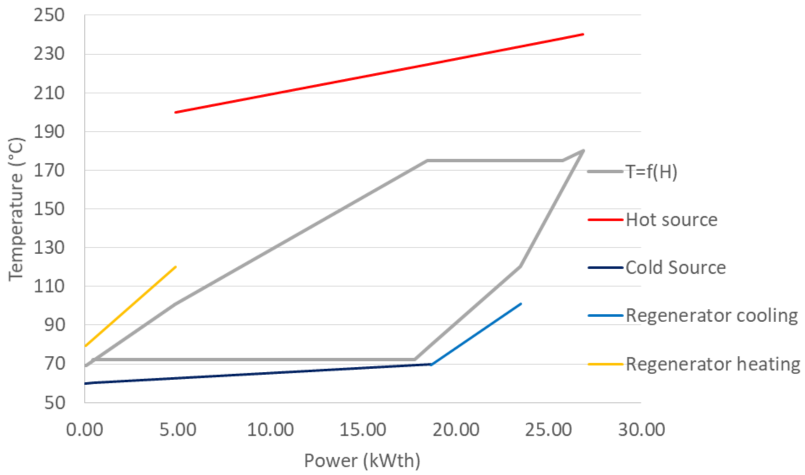

Figure 4: Updated thermodynamic cycle

3.3 Final layout of the prototype

Based on the new thermodynamic cycle, the whole system is being retrofitted.
First, new heat exchangers were selected in order to ensure the efficient transmission of heat power to the working fluid, with materials compliant with the fluid and temperature levels.
Then the fluidic path will be adapted to the needs in terms of mass flow rate and pressure ratio. As a result, the turbine mechanic assembly will be adapted. In particular, bearings and generator will be changed to match the new speed regimen.

The fluid cycle will then closed by choosing a new pump, adapting all sealings between the elements and refitting all the fluid lines.
All the elements will then be installed back on the skid, with the automat developed during the first test campaign.
The new system is expected to be operational for an extended test campaign before the end of the summer.

4. CONCLUSIONS

The first prototype of Innova microsolar allowed to gain a lot of understanding on the control of the overall system to produce flexibly electricity and water. This new campaign aimed at testing the machine in real conditions. The tests allowed highlighting a lower than expected production, and hinted a possible gain by changing the working fluid. It will allow increasing the working temperature, and the condensing pressure will remain higher than atmospheric pressure, at the cost of a higher environmental impact. An upgrading of the prototype has been prepared and is under way. This improvements should allow for a consequent increase in performances.

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