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Parametric multi-objective optimization of an Organic Rankine Cycle with thermal energy storage for distributed generation

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Abstract

This paper focuses on the thermodynamic modelling and parametric optimization of an Organic Rankine Cycle (ORC) which recovers the heat stored in a thermal energy storage (TES). A TES with two molten-salt tanks (one cold and one hot) is selected since it is able to operate in the temperature range useful to recover heat from different sources such as exhaust gas of Externally Fired Gas Turbine (EFGT) or Concentrating Solar Power (CSP) plant, operating in a network for Distributed Generation (DG). The thermal storage facilitates a flexible operation of the power system operating in the network of DG, and in particular allows to compensate the energy fluctuations of heat and power demand, increase the capacity factor of the connected plants, increase the dispatchability of the renewable energy generated and potentially operate in load following mode. The selected ORC is a regenerative cycle with the adoption of a Heat Recovery Vapour Generator (HRVG) that recovers heat from molten salts flowing from the Hot Tank to the Cold Tank of the TES. By considering the properties of molten salt mixtures, a ternary mixture able to operate between 200 and 400 °C is selected. The main ORC parameters, namely the evaporating pressure/temperature and the evaporator/condenser pinch point temperature differences, are selected as variables for the thermodynamic ORC optimization. An automatic optimization procedure is set up by means of a genetic algorithm (GA) coupled with an in-house code for the ORC calculation. Firstly, a mono-objective optimization is carried out for two working fluids of interest (Toluene and R113) by maximization of the cycle thermal efficiency. Afterwards, a multi-objective optimization is carried out for the fluid with the best performance by means of a Non-dominated Sorting Genetic Algorithm (NSGA) in order to evaluate the cycle parameters which maximize the thermal efficiency and minimise the heat exchanger surface areas. Toluene results able to give the best trade-off between efficiency and heat exchanger dimensions for the present application, showing that by with respect to the best efficiency point, the heat exchange area can be reduced by 36% with only a penalty of 1% for the efficiency.

Keywords: ORC; Organic Rankine Cycle, thermal energy storage, molten salts, optimization; genetic algorithm, distributed generation

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1. Introduction

Due to the current environmental needs, the European Commission has set for 2030 new targets aiming at improving the energy efficiency and reducing the greenhouse gas emissions [1]. In order to achieve these targets, the spreading of renewable energy plays a central role, together with the continuous improving of component efficiency [2]. The intermittency characteristic of renewable sources (such as solar, wind) introduces the need of managing the energy production by means of energy storage devices. Thus, in the last years the development of TES coupled with CSP represents a key topic in the scientific community [3], [4]. Indeed, CSP with TES devices are suitable to be integrated in distributed generation (DG) networks composed by different power blocks that can supply heat, power or both, as described in Figure 1. In this paper, the CSP plant is supposed to be integrated by an Externally Fired Gas Turbine (EFGT) fed by biomass. A potential candidate for recover energy from the thermal energy storage and convert it in electric energy is the ORC technology (Figure 2). To convert most efficiently the thermal input of the TES in electric power, we assume that the ORC generates only electric power. However, note that all the methodologies applied to this system can be easily extended to a different configuration that includes also heat generation.

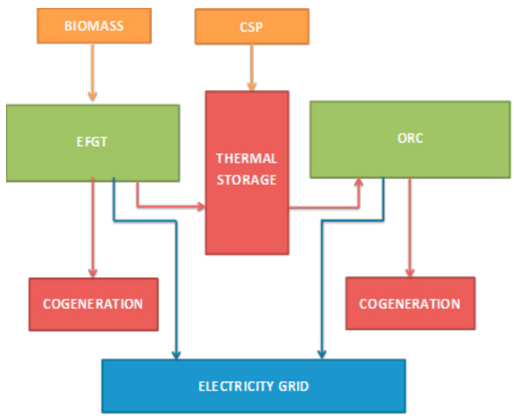

Figure 1 - Power blocks of the distributed heat and power plant

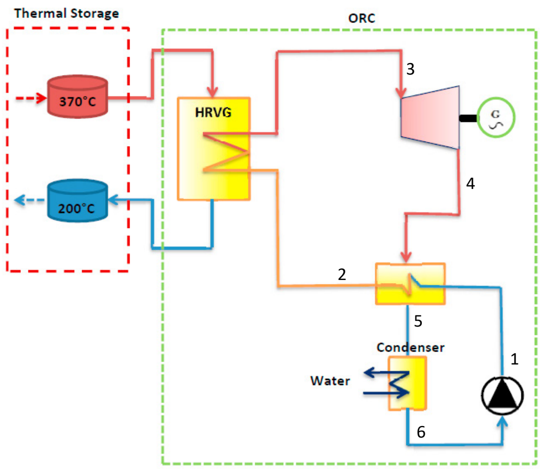

Figure 2 - ORC plant connected to TES

In ORC applications, the choice of the cycle parameters is of importance for improving the thermal efficiency and the exploitation of the thermal source. On the other hand, the expander and heat exchanger sizes influence the overall cost of the plant and a trade-off study for increasing efficiency and minimizing costs should be carried out. In this framework, the multi-objective optimization has gained interest as an efficient tool able to evaluate the best parameter configuration in the assigned design limits. Especially, the Non-dominated Sorting Genetic Algorithm (NSGA) [5] has been implemented in several thermo-economic analysis and parameter selection for ORC applications. Muhammad et al. [6] performed a multi-objective optimization of an ORC evaporator for low temperature geothermal heat source by minimizing the costs and the pressure drop. Aiming to improve the performance of the HRVG, numerical simulation of the flow through the banks can give a significant contribution [7]. The primary geometrical parameters of evaporator were selected as decision variables which included length, width and plate spacing. Muhammad et al. [8] showed the results of a thermo-economic optimization for a regenerative ORC for waste heat recovery applications. Maximum thermal efficiency and minimum specific investment cost were selected as objective functions and relative increase in thermal efficiency and cost were analyzed. In the mono-objective optimization framework, Wang et al. [9] applied a genetic algorithm to improve the system performance of an ORC for different working fluids, whereas Xi et al. [10] examined the performances of three different cycle configurations with six working fluids by using exergy efficiency as the objective function to maximize.

The paper is organised as follows: Chapter 2 describes the technologies adopted for the plant, including EFGT, solar plant and thermal storage and gives the thermodynamic analysis of the regenerative ORC plant assumed as reference first solution. Then, in Chapter 3, a preliminary mono-objective optimization by means of a genetic algorithm is carried out for the ORC plant, considering two fluids of interest: toluene and R113. By maximizing the thermal efficiency, the best set of cycle parameters (i.e. evaporation pressure, superheating and pinch point temperature difference in the evaporator) is evaluated. In Chapter 4, the fluid that shows the best efficiency is selected to perform a multi-objective optimization with NSGA in order to maximize the thermal efficiency and minimize the total surface area of the heat exchangers. An in-house code has been developed to calculate the regenerative ORC performance by implementing the CoolProp [11] libraries for the fluid properties calculation.

2. Technology description and hypotheses for the thermodynamic analysis

The detailed thermodynamic analysis of the EFGT is described in Ref. [12] and [13]. The EFGT is fed by biomass which produces a thermal input of 9050kWt at the rated LHV and produces a net electric power output of 1388kW while the available heat flow at the turbine exit is equal to 4093 kWt at 390°C. Therefore, the temperature of the Hot Tank of the TES has been accommodated to 370°C. The amount of thermal energy that can be recovered is 1890 kWt. The sensible heat can be further recovered for cogeneration, since the exiting air has still a temperature of 220°C.

The solar collector field is sized to supply 900 kWt and is based on ENEA technology of parabolic-trough concentrators (PTCs)[16][17][18][19]. Although this technology allows for temperature up to about 550 °C, in this work a lower temperature of about 390°C is considered in order to meet the temperature of the Hot Tank of the thermal storage. Further details of the plant can be found in Ref. [20].

Table 1 Basic calculation hypotheses for the ORC plant

Description	Value
Pump Isentropic Efficiency	0.75
Pump Mechanical Efficiency	0.96
Turbine Isentropic Efficiency	0.80
Turbine Mechanical Efficiency	0.96
Condenser temperature	40°C

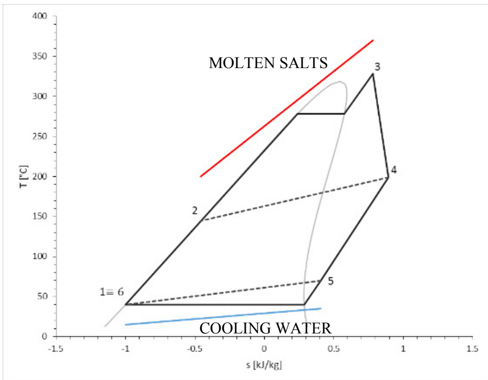

Figure 3 - T-s chart of the ORC plant.

The molten-salts mixture selected for the storage is composed by lithium salts, sodium and potassium nitrates. This mixture freezes at about 120°C and is liquid at temperatures higher than 200 °C [14]. For this reason, a temperature of 200°C is assumed for the cold tank. Under such hypotheses, the temperature difference between the two tanks is moderately higher than conventional systems that use oil as HTF (170°C instead of 100°C) and therefore allows for a lower volume for the two tanks [15].

The general calculation hypotheses for the ORC plant are summarized in Table 1. The total thermal input to the ORC has been assumed of 2790 kW_t. The thermal power input is transferred to the organic fluid in the HRVG from the two-tank molten-salt system in the range 370-200°C. Since heat is available at high temperature, a recuperative configuration is chosen for the cycle. A T-s diagram of the cycle is shown in Figure 3, where the red and the blue lines indicate the molten salts flowing in the HRVG and cooling water in the condenser, respectively. In the following Chapter, a mono-objective parametric optimization is carried out in order to find the best plant efficiency point.

3. Mono-objective parametric optimization strategy with different working fluids

The working fluids of interest for ORC applications are characterized by heavy molecules, high thermal capacity and low boiling point. Thus, the thermodynamic behavior is quite complex and can be accurately described only by equations that account for real fluid effects. In this paper, two organic fluids have been chosen: toluene and R113. The main physical properties are listed in Table 2 in terms of molecular weight M, critical pressure and temperature (p_c, T_c), ozone depletion potential (ODP) and global warming potential (GWP). The R113 is a refrigerant well known for its good performances in waste heat recovery [21], whereas toluene meets environmental and safety requirements. Besides, both fluids are chemically stable in the range of temperature considered in this work, as shown by the maximum allowable temperature before decomposition T_{max} (see Table 2).

Table 2. Working fluids physical properties

Fluid	M [kg/kmol]	p_c [bar]	T_c [K]	T_{max} [K]	ODP	GWP
Toluene	92.14	41.26	591.75	700	0	0
R113	187.38	33.92	487.21	787.5	0.9	6130

The parametric optimization of the ORC and the evaluation of the optimal set of the parameters of interest is performed in two steps by following the genetic (GA) and the Non-dominated Sorting Genetic (NSGA) algorithms for mono- and multi-objective optimization, respectively. In general, the genetic optimizations start from initial population, through genetic operator such as stochastic selection, mutation, crossover and evolve the population by selecting and combining the best individuals by following pre-defined selection criteria. During this process, the optimization parameters are varied until the global optimal value of the objective is found [4].

The mono-objective optimization by means of the genetic algorithm (GA) of the regenerative ORC is carried out with Toluene and R113 in order to maximize only the cycle thermal efficiency

$$\eta_I = \frac{\dot{W}_{exp} - \dot{W}_{pump}}{\dot{Q}_{in}} \tag{1}$$

where $\dot{W}_{exp}$ and $\dot{W}_{pump}$ are the expander shaft output power and pump input power, respectively, taking into account the isentropic and mechanical efficiencies defined in Table 1, while $\dot{Q}_{in}$ is the thermal input flow provided by the molten salts.

The fluid that provides the best performance, after the mono-objective optimization, is selected to perform the multi-objective optimization by means of the NSGA by maximizing η_I and minimizing $(UA)_{TOT} = (UA)_{HRVG} + (UA)_{RHE} = \dot{Q}_{in}/\Delta T_{lm,HRVG} + \dot{Q}_{rec}/\Delta T_{lm,RHE}$, where U and A are the thermal conductivity and surface area of the heat exchangers, respectively, and ΔT_{lm} the log mean temperature difference for the HRVG and RHE.

The optimization parameters are: the evaporation pressure p_{ev}, superheating $\Delta T_{TIT} = T_{TIT} - T_{ev}$ (where T_{TIT} is the turbine inlet temperature), and pinch point temperature difference for the HRVG, ΔT_{pp} .

The search for the optimal parameter set is carried out with the following constraints: $0.4p_c \leq p_{ev} \leq 0.9p_c$, $0 < \Delta T_{TIT} \leq (T_{hot\ tank} - T_{ev})$, $7\ K \leq \Delta T_{pp} \leq 10\ K$, $\Delta T_{min,RHE} \geq 5\ K$. Along with the best values of thermal efficiency and equivalent overall heat exchanger surface areas UA, other quantities of interest are evaluated:

- the exergy (second law) efficiency

$$\eta_{II} = \frac{\dot{W}_{exp} - \dot{W}_{pump}}{\dot{Q}_{in}(1 - T_0/T_m)}, \tag{2}$$

  where T_0 is the ambient temperature and T_m is the log-mean temperature given by

$$T_m = (T_{salt,in} - T_{salt,out})/\ln(T_{salt,in}/T_{salt,out})$$

  with $T_{salt,in}$ and $T_{salt,out}$ the inlet and outlet molten salt temperature, respectively;

- turbine size parameter $SP = \frac{\dot{V}_{out}{}^{0.5}}{\Delta h^{0.25}}$ (where $\dot{V}_{out}$, Δh are the turbine exit volumetric flow rate and enthalpy drop, respectively);

- fluid mass-flow rate $\dot{m}_f$;

- expander volumetric expansion ratio $V_r = \dot{V}_{out}/\dot{V}_{in}$ between the outlet and inlet volumetric flow.

The mono-objective optimization results are listed in Table 3 for the different working fluids. Convergence has been reached after 11 generations for each fluid, by considering a population of 200 individuals for each generation. It can be noticed that the optimization action, for maximizing the thermal efficiency, is devoted to increase the evaporation pressure and decrease the pinch point temperature difference in order to better exploit the thermal source. The best performance for the present application is provided by the toluene, with a maximum thermal and exergy efficiency of 30.3% and 64.3%, respectively. The R113 provides a thermal efficiency lower than toluene by 5.6 percent points, whereas $(UA)_{TOT}$ is 3.3 times higher. This result is explained by the temperature-heat power diagram in Figure 4. The R113 fluid is characterized by a lower critical temperature than toluene, then a longer path for superheating is required, thus resulting in a higher superheater exchange area. The electric generator losses are not considered in this analysis: depending on the technology they can be estimated equal to 5% of the turbine shaft power output; further energy losses are due to the electric consumption of auxiliary devices needed, e.g., for molten salts circulation, cooling water, evaporation tower, etc.; such losses can be roughly assumed equal to about 6% of the produced electric power.

For these reasons, in the following, the toluene is selected and analyzed for the multi-objective optimization.

Table 3. Mono-objective optimization results for the fluids of interest.

Fluid	p_{ev} [bar]	ΔT_{TIT} [K]	ΔT_{pp} [K]	η_I	η_{II}	SP [m]	V_r	$\dot{m}_f$ $[kg/s]$	UA [kW/K]
Toluene	21.27	51.45	7.06	0.303	0.643	0.205	220.16	4.73	125.93
R113	29.88	144.79	7.04	0.286	0.606	0.108	31.04	13.04	417.41

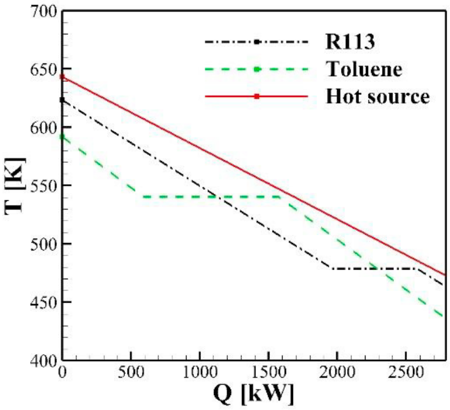

Figure 4. Temperature-Heat power diagram of the heat exchange in the HRVG for Toluene and R113 in the configuration optimized by mono-objective optimization (see Table 3).

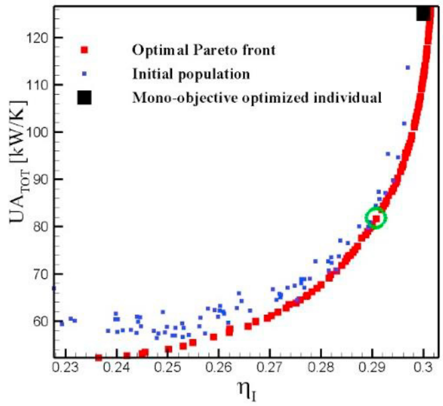

Figure 5. Pareto front (red squares) of the optimal individuals at convergence for the multi-objective optimization (fluid: Toluene). The initial population is marked with blue squares.

4. Results

In Figure 5, the multi-objective optimization results are shown as non-dominated individuals on the Pareto front. Convergence has been checked on the euclidean distance between the centroids of two successive Pareto fronts, and reached after 100 generations with 200 individuals for each generation. The multi-objective optimization provides a trade-off between the cycle efficiency η_I and overall heat exchanger cost. Indeed, without considering constraints about the surface areas, the mono-objective optimization evaluated the best parameter set for the highest efficiency but, on the other hand, $(UA)_{TOT}$ resulted very high, as shown in Figure 5 by the black square. A compromise solution could be selected on the Pareto front (green circle in Figure 5) where the efficiency is only 1% lower than the mono-objective optimal individual, but $(UA)_{TOT}$ is reduced by 36%.

Starting from this optimal configuration, it is possible to perform a sensitive analysis considering the parameter set of the multi-objective analysis shown in Table 4. In this paper, the effects of the evaporating pressure p_{ev} and and ΔT_{pp} on η_I and $(UA)_{TOT}$ are examined. Figure 5 shows that around the selected value p_{ev} =25.21 bar, efficiency η_I and $(UA)_{TOT}$ remain about constant. The increase of p_{ev} over 29 bar produces an increase of the thermal efficiency whereas $(UA)_{REC}$ increases very rapidly. For p_{ev} >32 bar (grey band), the value of ΔT_{rec} is lower than the value of 5K assumed as constraint in the optimisation search and for p_{ev} >35 bar there are no solutions since $(UA)_{REC}$ goes to infinity.

Figure 6 shows the effect of the pinch point temperature difference ΔT_{pp} in the HRVG that has a key role on the ORC cost since it influences the heat exchanger size. By increasing ΔT_{pp} in the range 7-10 K there is a decrease of $(UA)_{TOT}$ up to 20%, with a decrease of thermal efficiency by 1%. For higher values of ΔT_{pp} the loss of efficiency is too high with a lower rate of decrease of $(UA)_{TOT}$.

Table 4. Multi-objective optimization results for Toluene at the center of the Pareto front (green circle in Figure 4).

Fluid	p_{ev} [bar]	ΔT_{TIT} [K]	ΔT_{pp} [K]	η_I	η_{II}	SP [m]	V_r	$\dot{m}_f$ $[kg/s]$	UA [kW/K]
Toluene	25.21	50.05	8.36	0.292	0.614	0.197	256.17	4.4	82.2

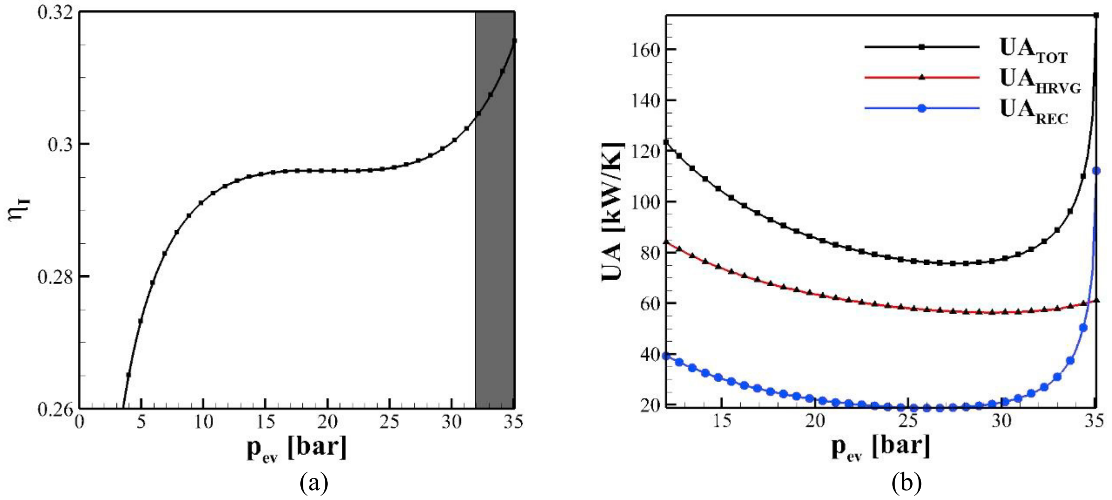

Figure 6. Influence of the evaporating pressure on the thermal efficiency and total equivalent heat exchange areas.

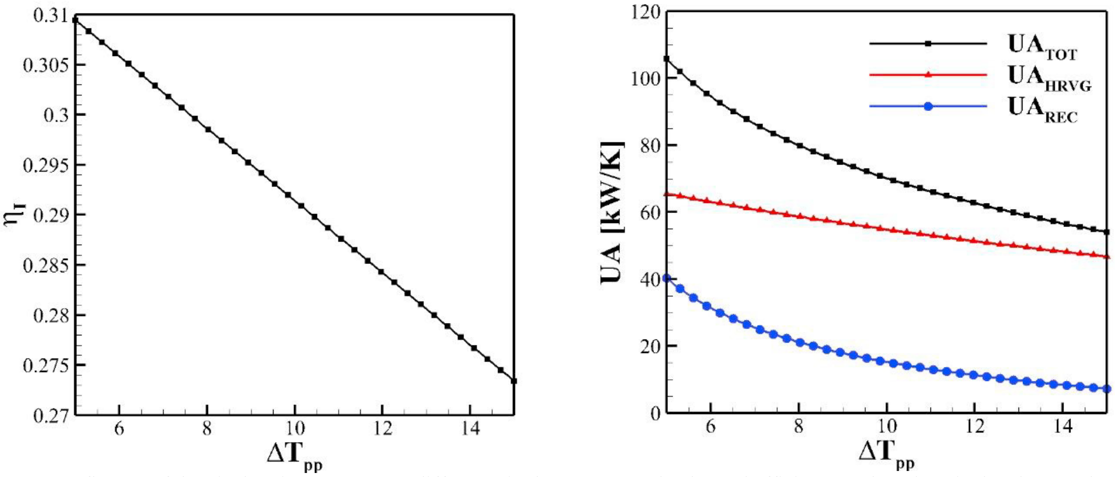

Figure 7. Influence of the pinch point temperature difference in the HRVG on the thermal efficiency and total equivalent heat exchange areas.

5. Conclusions

In this paper, a thermodynamic analysis, a mono-objective and multi-objective optimization have been performed on an Organic Rankine cycle (ORC) for Distributed Generation. The ORC plant is supposed to operate as power conversion unit of the energy stored in a two-tanks thermal energy storage, which operates in a range of temperatures from 200°C up to 350°C recovering heat an Externally Fired Gas Turbine exhaust gas and a solar field.

The mono-objective optimization aimed to maximize the thermal efficiency by varying the evaporating pressure, pinch point temperature difference and the turbine inlet temperature. It has been done for two different organic fluids, Toluene and R113, and the results showed that the most performing fluid is Toluene with a maximum thermal efficiency η_I =30.3%. The multi-objective optimization by means of NSGA has been carried out for the Toluene, by maximizing η_I and minimizing the sum of $(UA)_{HRVG}$ and $(UA)_{RHE}$, showing that by reducing of 1% the efficiency the $(UA)_{TOT}$ is reduced by 36%.

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