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Performance of a 5 kW_e solar-only organic Rankine unit coupled to a reverse osmosis plant

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Abstract

Organic Rankine Cycle (ORC) systems are one of the most promising energy conversion technologies available for remote areas and low temperature energy sources. An ORC system works like a conventional Rankine cycle but it uses an organic compound as working fluid, instead of water. A small ORC unit coupled with a solar thermal energy system could be used to convert solar thermal energy into electricity in remote areas, offering an alternative to Photovoltaic (PV) systems to provide the energy required by desalination applications like reverse osmosis (RO). In this work an analysis of the performance of a specific solar desalination ORC system at part load operation is presented, in order to understand its behavior from a thermodynamic perspective and be able to predict the total water production with changing operation conditions. The results showed that water production is around 1.2 m^3/h, and it is stable during day and night thanks to the thermal storage and only under bad irradiance circumstances the production would stop.

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Keywords: solar thermal; ORC; reverse osmosis

Nomenclature

A	Aperture area of the solar field	[m^2]
c_0	First term for the solar collector thermal efficiency curve	[-]
c_1	Second term for the solar collector thermal efficiency curve	[$Wm^{-2}K^{-1}$]
c_2	Third term for the solar collector thermal efficiency curve	[$Wm^{-2}K^{-2}$]

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I_{dir}	Normal Direct radiation	[Wm^{-2}]
K_{AP}	Pressure drop characterization parameter	[-]
$\dot{m}_{HEX-ORC}$	Mass flow rate from the tank to the ORC	[kgs^{-1}]
$\dot{m}_{SF}$	Mass flow rate of the solar field fluid	[kgs^{-1}]
$\dot{Q}_{HEX-ORC}$	Heat delivered to the ORC by the tank	[kW]
$\dot{Q}_{SF}$	Heat delivered to the tank by the solar field	[kW]
$\dot{Q}_{sun}$	Power from the sun that reaches the solar field aperture area	[kW]
T_{amb}	Ambient temperature	[ºC]
T_{co}	Average temperature of the collector	[ºC]
T_i	Temperature at i-th section of the tank	[ºC]
$T_{HEX\text{-}ORC,in}$	Temperature at the inlet of the evaporator of the ORC	[ºC]
$T_{HEX\text{-}ORC,out}$	Temperature at the outlet of the evaporator of the ORC	[ºC]
$T_{SF,in}$	Temperature at the inlet of the solar field	[ºC]
$T_{SF,out}$	Temperature at the outlet of the solar field	[ºC]
UA_{rec}	ORC recuperator heat transfer parameter	[W/K]
UA_{evap}	ORC evaporator heat transfer parameter	[W/K]
V_{dis}	ORC expander admission volume	[m^3]
VR	ORC expander volumetric expansion ratio	[-]
$W_{e,net}$	Net power produced by the ORC	[kW]
$\alpha, \beta, \gamma, \delta$	Condition functions	[-]
η_{SF}	Solar field efficiency	[-]
η_{PTC}	Parabolic trough collector efficiency	[-]
η_{ORC}	ORC efficiency	[-]
$\eta_{\exp}$	Expander efficiency	[-]
Φ	Incidence angle	[rad]

1. Introduction

For the development and survival of every society, the access to water is a basic need to cover. Unfortunately, it is not an essential covered everywhere. Obtaining potable water can be a challenge in remote and arid areas without regular power and supply. In those cases, a reverse osmosis system coupled by solar thermal energy can be a solution.

Organic Rankine Cycle (ORC) systems are one of the most promising energy conversion technologies for isolated areas and low temperature energy sources. An ORC system works like a conventional Rankine cycle but, instead of water, it uses an organic compound as working fluid. The use of this organic compound allows lower temperatures at the cycle without multistage expanders, providing good efficiency levels in less complex expanders. This technology aims to produce electricity from low-grade thermal energy sources, which may be either renewable energy or waste thermal energy from industrial processes.

Therefore a small ORC unit coupled with a solar thermal energy system could be used to convert solar thermal energy into electricity in remote areas, offering an alternative to Photovoltaic (PV) systems to provide the energy required by desalination applications like reverse osmosis (RO).

The small solar ORC systems are kW sized installations working at maximum cycle temperatures lower than 150 ºC. The use of conventional parabolic trough collectors (PTC), as the ones employed in solar power plants, is not adequate for these low capacity applications due to their complexity. In these cases, the best alternative is to use modular, small, lightweight and low cost PTCs [1].

Only a few solar ORC systems coupled to a RO unit have been investigated in previous scientific works but it is an interesting topic with rising interest [2-7]. Manolakos *et al.* [2] presented a pioneer theoretical and experimental research on this field, with an experimental evaluation of a low temperature solar organic Rankine cycle system for reverse osmosis desalination and evacuated tube solar collectors. The particularity of their system is that the RO unit high pressure pump is directly coupled to and driven by the expander of the ORC, where the mechanical work is produced. The results proved that their concept is technically feasible and continuous operation is achieved under discontinuous solar energy. However, they observed considerably low efficiency. Trying to improve these results, Kosmadakis *et al.* [3] proposed a two stage ORC for RO desalination. This system consisted in two cycles with different working temperatures. The heat extracted at the condensation of the high temperature ORC evaporates the refrigerant of the other. They evaluated this scheme economically and compared it to two alternatives of PV-RO systems. They concluded that the specific fresh water cost of their system was close to the PV-RO systems, and therefore, it was a competitive alternative desalination method. However, there are authors that don't agree with those conclusions. Delgado-Torres and García-Rodriguez [4] compared a single ORC with R245fa as working fluid with the cascade system operating between the same two temperatures and they concluded that the single ORC scheme would have a higher efficiency. Tchanche *et al.* [5] also argues that the cascade system does not increase the efficiency. Therefore, these authors claim that a single ORC configuration is a better choice when designing an ORC–RO system.

Most of the theoretical simulations of solar ORC consider a constant energy supply, without taking into account the variability of the solar thermal energy through dynamic models and none of them present a thermo-analysis of the part load performance of such systems. Nafey and Sharaf [6] presented a model to investigate solar driven large-scale desalination systems and they did performed energy and exergy analysis under two different operating conditions of the turbine inlet vapor, but the variability of the solar resource was not taken into account. Li *et al*. [7] proposed to increase the efficiency of the Solar ORC-RO system by using a supercritical ORC. They studied the performance of the power block under different operating conditions, and optimized the system efficiency as a function of the solar radiation. They concluded that the optimized system efficiency is greater than 18–20% for a wide range of irradiation values, and even at low solar radiation values the efficiency can reach 14%. Thus, further studies should be made for the solar ORC–RO systems, to determine the influence that the particularities of the solar energy have on the ORC off-design performance.

The objective of this work is to analyze the performance of a specific solar desalination ORC system at part load operation in order to understand its behavior from a thermodynamic perspective and be able to predict the total water production with changing operation conditions. To achieve this objective, a numerical model was developed. The on-design numerical model is used to calculate the reference cycle and its parameters. These parameters, along with the systematically varied working conditions, were used as inputs in the part-load numerical model of the cycle to assess the performance and losses of the plant.

2. Description of the model

The general scheme of the system proposed is shown on figure 1. The system has three main subsystems: the solar collector field, which transfers the solar heat into the working fluid; the thermal storage tank, which acts also as a buffer between the solar field and the power cycle; and the organic Rankine cycle, which transforms the thermal energy into electricity.

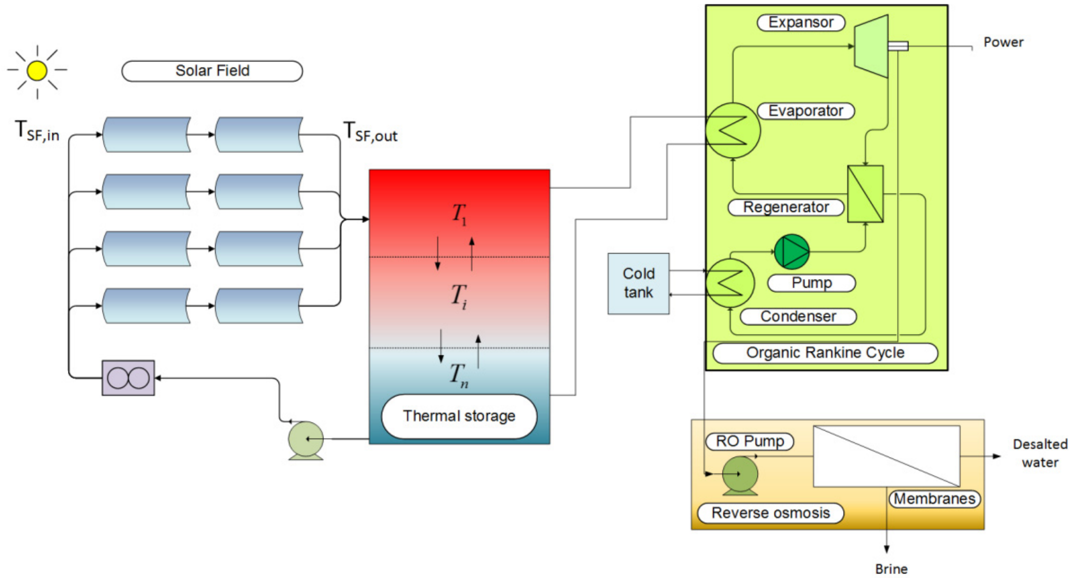

Fig. 1. General scheme of the process.

2.1. Solar collector field

The solar collector selected as more appropriate for the simulations was the collector commercialized by the Australian company NEP Solar, the Polytrough 1800 [8], whose properties are adequate for our purposes (table 1): low weigh, medium working temperatures and high efficiency.

Table 1. Properties for the NEPSolar Polythrough 1800 [8].

Property	Units	Value
Aperture area	m^2	18.450
Heat transfer fluid	-	Water
Glazing material	-	Borosilicate glass
Galzing thickness	mm	2.5
Absorber element	-	Stainless steel pipe
Coating	-	Black chrome
Absorber outside diameter	mm	34.0
Mirror	-	Aluminum
c_0	-	0.689
c_1	$W/(m^2K)$	0.36
c_2	$W/(m^2K^2)$	0.0011
K at 50º	-	0.93

The solar field has been designed for one day at summer to cover the heat demand of the ORC working for eight hours at the design conditions. As a result, it has three collectors in a row and three rows, with a total aperture area of 166.05 m^2 and an east-west orientation. Then, the performance of this solar field is determined for a whole year.

The calculated variables to analyze the solar field performance are the incident solar power on the field (Q_{sun}), the outlet power of the solar field (Q_{field}) and the thermal efficiency of the solar collector field (η_{field}). The incident solar power is measured in kW and is defined as the energy that strikes on the collector. It is calculated by the following expression:

$$\dot{Q}_{sun} = I_{dir} \cos(\varphi) A \tag{1}$$

where I_{dir} is the direct solar radiation, measured in W/m^2 and collected by a pyrheliometer and φ the incidence angle, determined through an algorithm that include date, time and location [9].

The outlet field power is measured in kW and is defined as the power provided by the field. It is calculated using the temperature difference between the inlet and the outlet of the thermal oil of the field, the thermal oil mass flow and the thermal oil specific heat through the following expression:

$$\dot{Q}_{SF} = \dot{m}_{SF} \times c_p (T_{SF,in} - T_{SF,out}) \tag{2}$$

The inlet of the field is determined by the energy thermal storage model. The oulet temperature of the field is calculated using its efficiency curve, where the parameters are given by NEP SOLAR and shown on table 1.

$$\eta_{PTC} = c_0 - c_1 \left(\frac{T_{co} - T_{amb}}{I_{dir}} \right) - c_2 I_{dir} \left(\frac{T_{co} - T_{amb}}{I_{dir}} \right)^2 \tag{3}$$

The efficiency of the field is calculated as the ratio between the total outlet power and the total incident solar power.

$$\eta_{SF} = Q_{SF} / Q_{sun} \tag{4}$$

2.2. Thermal storage

Solar energy is a time-dependent energy resource. Therefore, the storage of the energy produced is necessary to meet the energy needs of the ORC. The energy storage capacity of a water storage unit is calculated at uniform temperature. However, water tanks may operate with a significant degree of stratification, with the top of the tank hotter than the bottom. In this work a stratified multinode tank model has been chosen. The tank, with a total capacity of 10 m^3, has being divided into three nodes (or section) and the energy balance of each section is carried out considering it as fully mixed [10].

The fluid from the solar field enters at the top of the tank (node one) and the cold fluid directed to the solar field leaves from the bottom of the tank (node three), so that the maximum possible degree of stratification is preserved. It is assumed that the fluid streams flowing up and down from each node are mixed before they enter each node, before an energy balance on the nodes is done.

The energy balance for every i-th section of the tank is [10]:

$$M_i C_f \frac{dT_i}{dt} = \alpha_i \dot{m}_{SF} C_f (T_{SF,out} - T_i) + \beta_i \dot{m}_{HEX-ORC} C_f (T_{HEX-ORC,in} - T_i) + \delta_i \gamma_i C_f (T_{i-1} - T_i) + (1-\delta_i)\gamma_i C_f (T_i - T_{i+1}) - UA_i (T_i - T_{amb}) \quad (5)$$

where

α_i =1, if the fluid from the solar heat enters the first node, 0 otherwise

β_i =1, if the fluid returning from load enters node, 0 otherwise

$$\gamma_i = \dot{m}_{SF} \sum_{j=1}^{i-1} \alpha_j - \dot{m}_{HEX-ORC} \sum_{j=i+1}^{N} \beta_j$$

$$\delta_i = \begin{cases} 1 \leftarrow \gamma_i > 0 \\ 0 \leftarrow \gamma_i \le 0 \end{cases}$$

The equation 5 represents a set of first-order differential equations that can be solved analytically for the temperatures of the three nodes.

2.3. Organic Rankine Cycle

The model of the ORC is part load, using scroll and R245fa. First, an ORC cycle is calculated on the design point (see table 2) and its components are characterized. The characterization of the components requires the calculation of several parameters: the parameter $K_{\Delta P}$, characterizing pressure drop from the evaporator to the expander inlet; the admission volume (V_{dis}) and the volumetric expansion ratio (VR) of the expander; and the heat transfer parameter of the recuperator and the evaporator (overall heat transfer coefficient by the heat transfer area, UA_{rec} and UA_{evap}). These parameters allowed the calculation of the variables that reflect the operation behavior of the cycle at partial load operation.

Off-design simulation requires the prediction of the performance of the cycle elements at every operating condition, defined by the input variables. The input variables of the ORC model are the inlet temperature ($T_{HEX-ORC,in}$) and the flow rate ($m_{HEX-ORC}$) at the external side of the evaporator and the condensation temperature (T_{cond}), which is a function of the ambient temperature. As in the model describing the design point conditions, mass and energy balances are carried out in every component. The detailed description of the part load model of the ORC is not objet of this work, but it includes partial performance of the expander, through a scroll expander model based on the work of Lemort *et al*. [11], the recuperator and the internal evaporator. This model allows the calculations of the power produced by the ORC at different inputs and the thermal efficiency of the cycle.

$$\eta_{ORC} = \frac{W_{e,net}}{Q_{HEX-ORC}} \quad (6)$$

Where $W_{e,net}$ is the net mechanical power out of the ORC and $Q_{HEX-ORC}$ is the thermal power provided at the evaporator.

Table 2. Properties of the ORC on its design point

Property	Units	Value
Working fluid	-	R245fa
$T_{HEX\text{-}ORC,in}$	ºC	155
$\dot{m}_{HEX-ORC}$	kg/s	0.3303
P_{evap}	kPa	2080.5
P_{cond}	kPa	147.43
T_{high}	ºC	145
$\dot{m}_{ORC}$	kg/s	0.1467
η_{ORC}	-	0.1422
$W_{e,net}$	kW_e	5

3. Methodology

The study of the performance of the solar-only organic Rankine cycle coupled to a reverse osmosis system was carried out using a typical meteorological year for Almeria, located at the south of Spain. The variables selected within the meteorogical data were the normal direct radiation and the ambient temperature. The data is given for every hour and hence, the performance of the whole system was calculated every hour as well.

The climatic variables determine the solar field performance, which defines the temperature level of the thermal storage tank. The temperature level of the tank determines the performance of the ORC. For the performance of the solar cycle the variables studied were the efficiency of the field, the power delivered to the tank and the inlet and outlet temperature. For the tank, the variables studied were the mean temperature and the power saved. For the cycle performance, the variables studied were the thermal efficiency (η_{th}), the net power (W_e) and expander isentropic efficiency (η_{exp}). Finally, for the reverse osmosis production, the water production was considered. For the calculation of the power required by the desalination plant, a specific electric consumption of 4 kWh/m^3 [12].The results of these simulations are shown in next section.

The simulation model was implemented in Matlab 2012b [13] and the properties of the fluid were obtained using the Refprop libraries for R245fa [14,15].

4. Results

Three day three days of summer and three days in winter were selected as reference. The results for those six days are shown in figures 2 (for the summer time) and 3 (for the winter time). For each of those figures, the subfigure in the left represents the power performance of the system: the solar direct radiation, the power produced by the solar field, the power delivered by the solar field to the tank. Below, and at a different scale the power produced by the organic Rankine cycle is shown. On the right, the efficiencies of every subsystem along the three days are shown: the efficiency of the solar field, the efficiency of the organic Rankine cycle, the efficiency of the ORC expander and the total efficiency. Below, the water production of the RO system is presented.

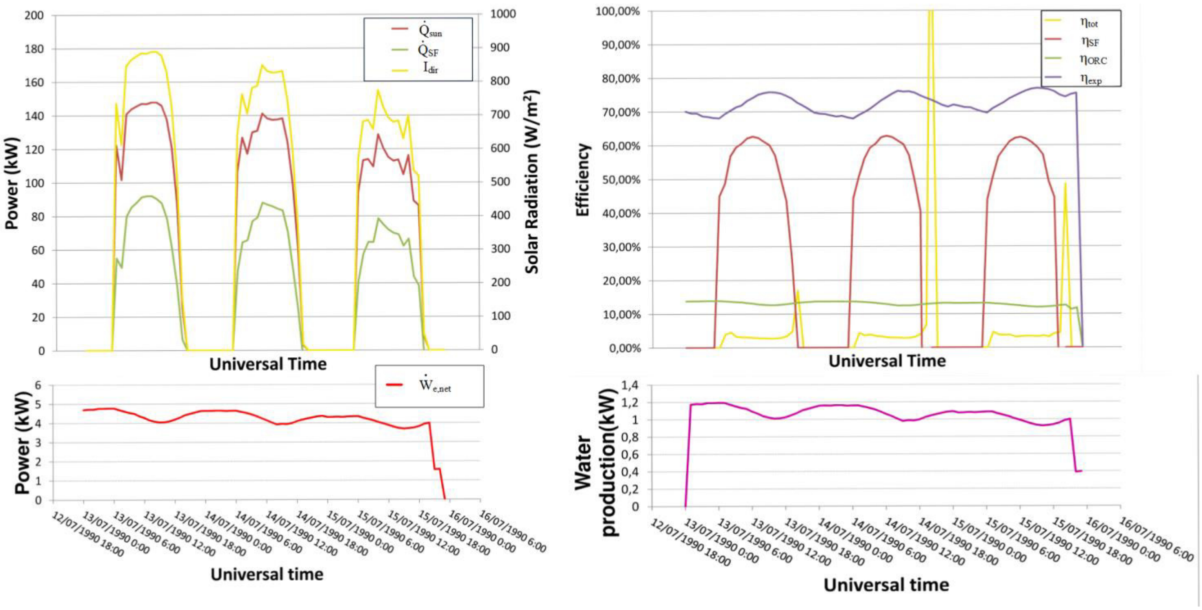

Fig. 2. Performance of the system during the three days in summer.

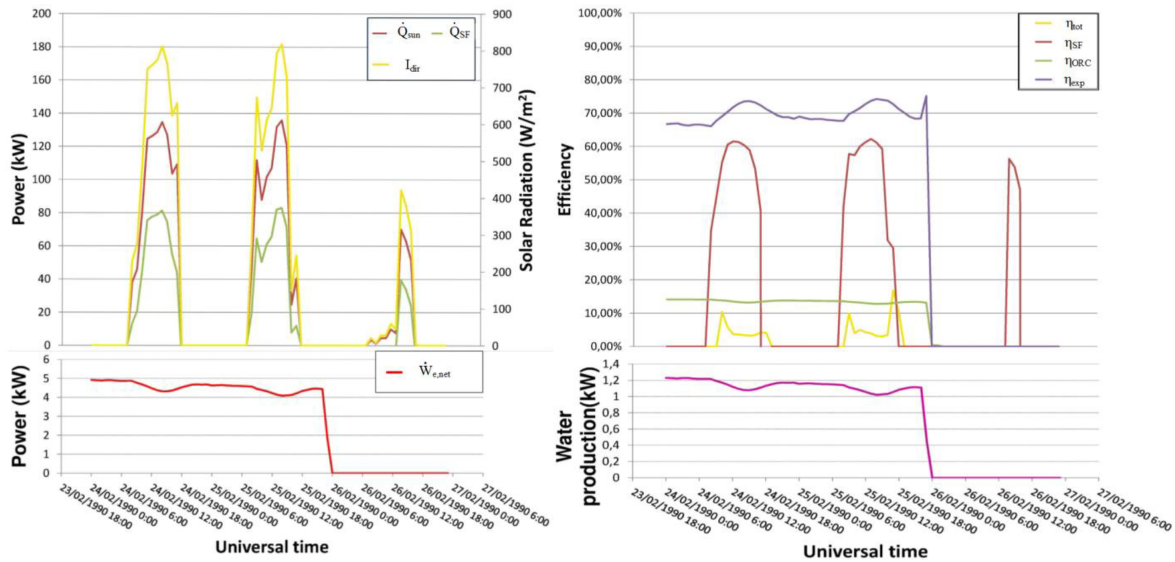

Fig. 3. Performance of the system durign the three days in winter.

For the summer time, the radiation was good and, therefore, the power production by the field was very good. The power production of the ORC was stable during the three days (and nights). This stable power production allowed stable water production too. In contrast, for the winter time the radiation was low on the third day and as a direct consequence, the ORC operation was interrupted (and hence the water production too) because the temperature in the tanks was below the minimum set point limit.

The efficiency of the solar field reached 60 % if the radiation were good, with minor differences between summer and winter due to the east-west orientation. The efficiency of the ORC was stable during all day, regardless of the solar resource. The efficiency of the expander, however, was better when solar energy available was stable, because the temperature that reached the heat exchanger would be higher if the solar field was providing constant energy. The global efficiency value was always below 7 %. At the beginning and the end of the operation of the solar field there were some peaks in the efficienciy because at those moments the ORC was producing stable power using the heat stored in the thermal tank but the solar field was still providing very little heat to the tanks.

The water production was around 1.2 m^3/h, and it was stable during day and night thanks to the thermal storage and only under bad irradiance circumstances the production would have to stop.

5. Conclusions

This work has presented the analysis of the performance of a specific solar desalination ORC system at part load operation. The objectives were to understand its behavior from a thermodynamic perspective and be able to predict the total water production with changing operation conditions. Some important conclusions are summarized below:

- The use of an organic Rankine cycle is an alternative thermal desalination technology incorporating the RO desalination process.
- The organic Rankine cycle can use the heat delivered by a solar collector field, if a thermal storage is provided. Operation in partial load was also feasible, and the power production did not fluctuate during the day.
- The water production was around 1.2 m^3/h. This value may seem unsatisfactory compared with the complexity of the system. However, we should take into account that this kind of systems is aimed to remote areas where the access to electricity and water is a challenge.

In conclusion, ORC can be used efficiently to recuperate solar power and produce fresh water especially in remote areas with the need for fresh water and high irradiance values.

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