Investigation of Multiple Reverse Osmosis Sub-Units Coupled to a Small-Scale Solar Subcritical Organic Rankine Cycle Engine

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Abstract
A small-scale low-temperature solar Organic Rankine Cycle (ORC) for seawater desalination is investigated with a maximum capacity of around 2 m³/h fresh water production. The heat input to the ORC is provided by evacuated tube solar collectors, while the net power produced by this subcritical cycle feeds a Reverse Osmosis (RO) unit. The main focus here is given on the configuration of the RO unit, composed of three identical sub-units, which are switched on/off, according to the power availability, in order to operate within their operating range, thus with high efficiency and acceptable fresh water quality.

The ORC engine is equipped with two in-series scroll expanders, in order to keep acceptable expansion efficiency for the whole operating load (decided by the incident solar radiation and ambient temperature), while the first expander is by-passed at low loads, securing an adequate power availability of the RO unit. A critical aspect examined here is the coupling of this two-stage ORC engine with the RO unit, and more precisely how the available power is used in the three RO sub-units, equipped with energy recovery units, and concluding to the dependence of the fresh water production and specific energy consumption from the weather conditions.

Keywords: reverse osmosis, solar energy, organic Rankine cycle, membrane pressure

List of symbols

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>$dP_{APM}$</td>
<td>pressure difference at the axial piston motor (bar)</td>
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<tr>
<td>$dP$</td>
<td>pressure difference at the HP pump (bar)</td>
</tr>
<tr>
<td>$P_e$</td>
<td>power input to the RO unit from the ORC (W)</td>
</tr>
<tr>
<td>$P_{APM}$</td>
<td>power recovered by the axial piston motor (W)</td>
</tr>
<tr>
<td>$P_{APP}$</td>
<td>power of the axial piston pump (W)</td>
</tr>
<tr>
<td>$Q_{BR}$</td>
<td>brine flow rate (m³/h)</td>
</tr>
<tr>
<td>$Q_{SW}$</td>
<td>feed seawater flow rate (m³/h)</td>
</tr>
<tr>
<td>$T_a$</td>
<td>ambient temperature (°C)</td>
</tr>
<tr>
<td>$T_{SW}$</td>
<td>seawater temperature (°C)</td>
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1. Introduction
Several research studies deal with the design and operation of power plants, which are based on the Organic Rankine Cycle (ORC) technology [1-3]. This intense investigation is justified, since the ORC process is appropriate for converting low-temperature heat to power [4]. The heat sources can be industrial waste heat [5], solar thermal energy [6], geothermal energy [7], or even biomass [8]. Moreover, such ORC units can be

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constructed from the kW up to the MW scale, providing a high flexibility on the application of concern, although most of such systems are of small/medium scale and applied in cases, where the steam Rankine cycle is inappropriate (due to the small scale and low available temperature).

Especially for solar energy applications, there are numerous studies, proving the importance and cost-effectiveness of such energy systems [9-12]. Most of these works focus on the power production from the ORC module, which is then converted to electricity, while few others focus on using the produced power to drive Reverse Osmosis (RO) desalination units [12, 13]. In both cases, the same critical aspects are investigated, such as the design of the ORC [1, 2], the selection of the organic fluid [4], and the coupling and control of the operation [5]. These aspects are of high importance and each one can contribute to the efficiency maximization of the system or preferably the maximization of the net power production.

The system under investigation uses a solar field of evacuated tube collectors, feeding with heat a subcritical ORC engine for power production, and then driving a RO unit. The RO unit is composed of three identical RO sub-units, in order to increase the flexibility of the system due to the solar energy intermittency, while each sub-unit is equipped with energy recovery unit for decreasing the specific energy consumption. The operation of these three sub-units is investigated and the characteristics of such configuration are given for variable weather conditions, since the RO performance at part-load operation is a very important issue, especially in solar desalination applications. The characteristic curves of the membranes and the high-pressure pump are presented, depicting their effect on the RO performance, which decreases at off-design conditions [10, 14], and producing water of low quality. Such aspect can be significantly overcome with the alternative design followed here.

2. System, components and methods

2.1. System description

The heat input to the small-scale low-temperature Organic Rankine Cycle (ORC) for seawater desalination is provided by evacuated tube solar collectors with a maximum capacity of 100 kWth at around 130 °C, while the power produced by this subcritical ORC feeds a RO unit for desalinating seawater. The heat transfer fluid (HTF) in the collectors’ circuit is pure monoethylene glycol (MEG), having a boiling temperature over 190 °C and good heat transfer characteristics [15, 16], while the HTF mass flow rate is regulated, by changing the rotational speed of the feed pump (of centrifugal type), using an asynchronous motor and a frequency inverter, in order to maximize the heat input to the ORC.

An important feature of this ORC engine, using the organic fluid R-245fa, is the use of two scroll expanders, installed in series [15, 16]. Such configuration is followed, in order to keep acceptable expansion efficiency for the whole operating load (decided by the incident solar radiation and ambient temperature). By doing so, the pressure ratio of each expander varies within a narrow range (from 2 up to 4). At high load (total pressure ratio around 9) both expanders operate, while at lower heat input from the solar collectors (for lower organic fluid evaporation temperature/pressure and for total pressure ratio of 3-4), the first expander is totally by-passed and only the second one operates. The main concern is to maximize the power availability, feeding the RO unit [2]. The expanders used are hermetic scroll compressors operating in reverse, having high expansion efficiency for a wide range of pressure ratio (usually from 2.5 up to 5), and are of low cost [17], while they show their maximum expansion efficiency for pressure ratio equal to around 3-4. Further details on the operation and optimization of the two-stage ORC engine and its alternative design can be found in Ref. [16], where its performance is investigated for various operating conditions.

A critical aspect examined here is the coupling of the two-stage ORC engine with the RO unit, and more precisely how the power availability is used in the three RO sub-units, equipped with energy recovery units (axial piston motors – APM). The RO sub-units are switched on/off, according to the power availability. This strategy is followed, in order to operate each sub-unit within its operating range, thus with high efficiency and acceptable fresh water quality. Their operation is investigated for variable power input, in order to examine their operational characteristics. Then, these three sub-units are synthesized, in order to form the complete RO unit, concluding to the dependence of the fresh water production and specific energy consumption from the weather conditions [6, 12]. Next, the developed RO configuration is described.
Due to the large variation of the power input from the ORC, some flexibility in the RO operation is required, leading to higher efficiency and better water quality. Therefore, the use of three identical RO sub-units has been selected, whose operation depends on the power availability from the ORC, and they can be switched on/off accordingly. With such configuration, although the control complexity increases, the combined unit can operate with very low total dissolved solids (TDS), around 200-250 ppm, for most of the operating conditions, with specific energy consumption around 3.5 kWh/m³ and water recovery of 32%.

Each RO sub-unit includes a feed pump, filters, high-pressure (HP) pump (axial piston pump – APP), energy recovery unit (axial piston motor – APM, coupled on the same shaft with the HP pump), frequency inverter, membranes and membrane vessels. Such combined configuration is depicted in Fig. 1.

Since the energy recovery unit is coupled on the same shaft with the HP pump and the electric motor, having a common rotational speed, Eqs. (1)-(3) can be used to describe the power conservation of the system [18, 19].

\[
P_e + P_{APM} = P_{APP}
\]

\[
P_{APP} = \frac{Q_{SW} dP}{n_{APP} n_{el}}
\]

\[
P_{APM} = Q_{BR} dP_{APM} n_{APM}
\]

where \(P_e\) the power input to the RO sub-unit from the ORC, \(P_{APM}\) the power recovered by the axial piston motor, \(P_{APP}\) the power of the HP pump for pressurizing the feed seawater (for simplicity, it also includes the feed pump power), \(Q_{SW}\) the feed seawater flow rate, \(dP\) the pressure difference at the HP pump (equal to around 50-60 bar), \(n_{APP}\) the efficiency of the axial piston pump set equal to 90%, \(n_{el}\) the electrical efficiency of the axial piston pump equal to 86%, \(Q_{BR}\) the brine flow rate (equal to around 68% of the seawater flow rate, since the water recovery is 32%), \(dP_{APM}\) the pressure difference at the axial piston motor (its outlet is equal to the ambient pressure, while its inlet is around 1.5 bar lower than the membrane pressure), and \(n_{APM}\) the efficiency of the axial piston motor equal to 75% [20].
The maximum fresh water production is around 2.1 m³/h, when the power availability from the ORC is 9 kW (for incident solar radiation equal to 1000 W/m²) [16]. At this case all three sub-units are operating. The main performance values of the RO sub-unit are calculated using ROSA v.7.2.7 software [21] for an inlet seawater temperature equal to 20 °C and a typical TDS equal to 42000 mg/l, while the membranes used are of SW30-4040 type [22] (2 in-series membranes in each vessel, 2 vessels in total).

The performance of each RO sub-unit can be then simulated, while the correlations of the most critical parameters, such as the membranes pressure, flow rate, power input, etc., are extracted and used in the main simulation program built under the EES environment [23]. The main operational data of the RO configuration are depicted in the left hand side of Fig. 2, where the membrane pressure is observed as a function of the inlet seawater flow rate. The correlation between the seawater flow rate and the HP pump rotational speed for each RO sub-unit is observed in the right hand side of Fig. 2.

From the left hand side of Fig. 2 is concluded that the correlation between the membrane pressure and the seawater flow rate is linear. At the maximum flow rate allowed, the membrane pressure takes its maximum possible value, assuring a good quality of the desalinated water. Moreover, the control of the seawater flow rate is achieved with the frequency variation of the electric motor of the HP pump, using an inverter, controlling its rotational speed (maximum speed of 3500 rpm) and regulating the seawater flow rate, as shown in the right hand side of Fig. 2. It should be mentioned that the seawater feed pump operates at constant speed, but with variable outlet pressure, since it is not essential to control its operation. By doing so, the regulation of the system becomes simpler.

3. Results and discussion

The study focuses on the RO system results, while the power production components (solar field and ORC engine) are not studied, since their detailed investigation has been conducted in a recent published work [16]. The results section begins with the investigation of performance of each RO sub-unit, while then they are synthesized, in order to examine the seawater desalination capability as a function of the weather conditions.

3.1. RO sub-unit operation

In this section, the operation and performance of each RO sub-unit is investigated. Focus is also given on their switchable operation, according to the available power input from the ORC engine. The characteristics curve of the membranes is shown in Fig. 3. This Figure actually correlates the feed pressure with the inlet
seawater flow, enabling the calculation of the operating condition of each sub-unit. The quality of the produced water is also shown.

![Graph showing feed pressure and salinity as a function of feed flow rate](image)

Fig. 3. Feed pressure and salinity as a function of the feed flow rate for each RO sub-unit

The membranes pressure is almost linearly correlated to the feed flow rate, while the salinity rapidly decreases as the flow rate increases [24, 25]. Acceptable quality of fresh water (lower than 500 mg/l) is observed for feed seawater flow rates higher than around 1 m³/h, while the membrane pressure can reach even 62 bar.

The correlation of the membrane pressure with the specific energy consumption and the power required is shown in Fig. 4.

![Graph showing specific energy demand and HPP power](image)

Fig. 4. Specific energy consumption and required power of each RO sub-unit as a function of the membrane pressure

At low membrane pressure, the specific energy consumption significantly decreases, but the disadvantage at this case is that the produced fresh water is of low quality (higher than 500 mg/l). Therefore, the investigation of the operation of each RO sub-unit is not only relevant to the power requirement, but also to the quality of the produced water.

A more detailed view of the characteristic curve of the HP pump is depicted in Fig. 5, where the feed flow rate and power consumption can be observed for different rotational speeds. This Figure considers the membrane pressure as a free parameter, while showing that the required HP pump power is linearly correlated to the rotational speed, and it increases for higher membrane pressure, as expected.
The RO sub-unit operating condition for a given power input from the ORC can be calculated, when the characteristic curves of both the membranes and the HP pump are taken into consideration. Their combined operation gives the final values of the feed flow rate and membrane pressure. This can be easily accomplished, if the configuration is finalized. Such method is depicted in Fig. 6, where the operating condition is actually the cross-sectional of two curves. One curve corresponds to the characteristic curve of the membranes and the other to the HP pump, while each set of curves corresponds to different power input from the ORC (1-3 kW).

It can be observed that for low available power (1 kW, see left Fig. 6), the membrane pressure is less than 50 bar, while the seawater feed flow rate is around 1 m³/h. The membrane pressure rapidly increases for higher power input (see middle Fig. 6), since the design operating condition is approached. For power input equal to 3 kW, the seawater feed flow rate is just higher than 2 m³/h, while the membrane pressure is around 58 bar.

These correlations can be extended, concluding to Fig. 7, where the specific energy consumption can be observed as a function of the available power input for each RO sub-unit. In the same Figure, the fresh water TDS is also shown.

It is observed that the TDS level has a steep variation at low available power, where the specific energy consumption is also low, since the membrane pressure is much lower than the designed one [26]. For available power of 1 kW and higher, the TDS level holds acceptable values lower than 400-500 mg/l, which is achieved with the high pressurizing of the feed seawater, increasing accordingly the specific energy consumption up to values of 3.5 kWh/m³.
Fig. 7. Specific energy consumption and fresh water TDS of each RO sub-unit for variable power input from the ORC engine

Finally, the switching on/off of each RO sub-unit, according to the power availability from the ORC engine, can be observed in Fig. 8.

![Fig. 8. Operation of RO sub-units as a function of the ORC net power input](image)

It is observed that for power production up to around 3 kW, only one RO sub-unit operates. For higher power production, the second and then the third sub-unit are successively engaged, offering a high flexibility during the part load operation. Moreover, even at very low load (e.g. at 20% of the full load, for around 2 kW), the performance of the desalination unit is adequate, producing water of acceptable quality with low specific energy consumption.

3.2. RO system

In the previous section, the performance and operation of each RO sub-unit has been investigated. Here, the previous results are synthesized, in order to examine the performance of the RO system as a whole, and its coupling with the ORC engine. In Fig. 9 is depicted the performance of the RO system for the whole range of power input from the ORC. It can be clearly seen that when the ORC power is 3 and 6 kW, the second and third RO sub-unit are switched on respectively. This transition is not smooth, since at the beginning of their operation the fresh water TDS is high (see Fig. 7), increasing the mixture TDS, while the specific energy consumption is low (see Fig. 7), reducing the overall value.
For ORC power input higher than 3 kW, the specific energy consumption is almost constant and equal to 3.5 kWh/m³, while the fresh water TDS has small variations and is approximately equal to 200-250 mg/l. For very low ORC power input, although the specific energy consumption is low (due to the low membrane pressure), the fresh water TDS is very high. Only for power input higher than 1 kW has the fresh water acceptable quality.

Finally, the RO system operation depends on the power availability from the ORC, while the performance of the latter depends on the weather conditions. Therefore, a direct correlation of the RO system performance with these weather conditions is attempted, in order to identify the overall performance of such system. This is implemented for three different values of the ambient temperature ($T_a$) and for the whole range of incident solar radiation. The calculated results are depicted in the left Fig. 10, while in the right Fig. 10 similar results are shown as a function of the available heat input to the ORC from the solar field.

It can be observed that the fresh water production closely follows the solar radiation, since, as was mentioned previously, by using three identical RO sub-units the overall performance of the RO system is almost constant even at part load operation. For solar radiation lower than around 300 W/m², there is no actual power production, since the ORC evaporation temperature and pressure are very low [16]. For higher solar radiation, the combined system starts operating, with only one RO sub-unit switched on, up to around 500 W/m² (around 35 kWₘₐₜ), where the operation of the second RO sub-unit is initiated. The third sub-unit is switched on at 750 W/m² (around 60 kWₘₐₜ), in order for the three sub-units to produce a total of around 2.5 m³/h at full load (at
solar radiation equal to 1000 W/m², at around 80-90 kWth).

In case the incident solar radiation is even higher than 1000 W/m², the HP pumps will continue to operate with constant flow rate, since the membranes and pumps will have reached their maximum capacity, but the membrane pressure will slightly increase, producing water of even lower salinity and higher quality, increasing accordingly the specific energy consumption. It should be mentioned that as the ambient temperature decreases, more water is desalinated, since the ORC unit performs better at such conditions, due to the use of an air-cooled condenser [16], although the available heat is significantly lower (decrease of the solar collectors efficiency).

4. Conclusions

In the present work, a small-scale solar ORC for seawater desalination was investigated. Attention was given on the three identical RO sub-units and their switchable operation, according to their power consumption. The operation of each RO sub-unit was examined during the load variation of the ORC engine. Focus was given on the performance values, when the membrane pressure and feed flow rate change, due to the variable power availability. Then, the RO system performance was identified by the synthesis of these three sub-units, while the dependence of the fresh water production from weather conditions and the heat transferred to the ORC was presented.

The present study focuses on the RO desalination units at variable load operation, suggesting an alternative configuration that could be utilized especially for small-scale systems supplied by solar energy, offering flexibility and securing an acceptable fresh water quality at almost all weather conditions. Such aspect is very important, in order to further improve such integrated systems and conclude to alternative designs, which can increase their performance and at the same time reduce their specific water costs, enabling them to further proceed to pre-commercialization stage.

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References