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ABSTRACT

Transcritical organic Rankine cycle (transcritical ORC) systems have the potential to achieve high heat-to-power performance for low-grade heat sources. In these systems, heat addition to the working fluid occurs under supercritical conditions, offering a way to improve the efficiency (compared to a subcritical ORC). In literature, several theoretical studies can be found, discussing efficiency improvement and performance of the overall cycle, the performance of the individual components and thermo-economic optimization. However, very few experimental campaigns have been carried out on an actual installation. Therefore, it is difficult to assess how such a system works under actual field conditions and what performance and efficiency it can reach in practice. In this paper, results are discussed from field tests that were performed on a small-scale transcritical ORC engine coupled with Concentrating Photo Voltaic Thermal (CPVT) collectors, which produce the heat that is provided to the ORC unit. Transcritical operation is discussed and a comparison is made to subcritical operation. In addition, the performance of the expander is extensively investigated. Based on the results presented in this paper, the potential of practical transcritical ORC engines for low-grade heat conversion is discussed and insight is given into the performance of the current scroll expander. A maximum thermal efficiency of 2.2% was measured under transcritical conditions. While this is low compared to normal subcritical operating conditions, this efficiency is in line with the few experimental data that have been previously reported in literature. The main factor causing this low efficiency is the low part-load performance of the current scroll expander. The maximum expander rotational speed that could be set without leaving the transcritical operating region was 22.5 Hz, which is only half of the nominal rotational speed. Future work includes performing experiments at higher expander rotational speeds and evaluating the supercritical heat exchanger performance based on the current measurements.

1. INTRODUCTION

In order to reduce greenhouse gas emissions and limit the impact of electricity production on the climate, sustainable energy sources (compared to conventional fossil fuels) are becoming increasingly important. Conversion of heat sources such as solar, geothermal and waste heat will play a major role in this greener power production. However, as these heat sources consist of low-to-medium temperature heat, alternative heat-to-power cycles with alternative working fluids are required (instead of the well-known steam Rankine cycle). Organic Rankine cycles (ORC) are mature and commercially available systems that can serve as a possible solution. However, there is still room for improvement as the efficiency of these systems is rather limited. Operating the ORC under transcritical conditions (i.e. transcritical ORC (TORC)) offers a way to improve efficiency. In a TORC, the heat transfer to the working fluid takes place under supercritical conditions, reducing heat transfer losses and enabling increased cooling of the heat source (Schuster *et al.*, 2010). Several papers can be found in literature which discuss the theoretical efficiency improvement and performance of the overall cycle, the performance of the different components or thermo-economic optimizations, but very few experimental measurement campaigns have been performed on an actual installation (Lecompte *et al.*, 2015). This information is however important in order to assess how such a system works under practical conditions and what performance and/or efficiency can be reached in reality. An overview of the experimental work done on ORCs operating under transcritical conditions and the main findings are provided by Lecompte *et al.* (2019). In total, only four references on small-scale transcritical ORC systems (Kosmadakis *et al.*, 2016b; Landelle *et al.*, 2017; Hsieh *et al.*, 2017 and Demierre *et al.*, 2015) and three on large-scale systems were mentioned.

Solar energy has a huge potential as renewable energy source for power production, as in theory only a small fraction of the solar radiation has to be captured in order to cover the global energy demand (Golonis *et al.*, 2021). However, solar ORC applications are limited (<1% of installed capacity). This is mainly because of the high investment cost of a solar collector field (compared to photovoltaic panels connected to battery systems) (Tartière and Astolfi, 2017). Hybrid systems, such as combining ORC technology with Concentrating Photo Voltaic Thermal (CPVT) collectors could make the technology more interesting. Thorough techno-economic evaluations have to be performed before these systems can be installed and further improving ORC efficiency is also key in making them more attractive (Golonis *et al.*, 2021). Kosmadakis *et al.* (2016a) gave an overview of the experimental small-scale low-temperature ORC installations and stated that even though the majority is dedicated to solar installations, only a few have actually been tested when coupled with the solar field. Therefore, the authors performed measurements on an ORC test rig connected to concentrating PVT collectors, where they executed both lab and field tests. Results in the subcritical and some in the transcritical region were discussed. For operation under transcritical conditions, the exergy destruction in the supercritical heat exchanger is significantly lower than under subcritical conditions (due to higher pressure, the mean temperature difference between the heat transfer fluids is reduced). However, the exergy destruction in the condenser, expander and pump is higher. In another work, Kosmadakis *et al.* (2016b) performed lab tests on the described ORC engine, both in the subcritical and transcritical region. Transcritical conditions could only be reached for very low expander speeds and very high pump speeds, resulting in low expansion efficiency. However, they stated that if expansion efficiency could be increased (e.g. by changing to a smaller expander), thermal efficiency at transcritical condition could be higher than the one at subcritical conditions. Golonis *et al.* (2021) focused on the subcritical operation, where performance maps are created for the variable solar irradiance with the main control variables being the rotational speeds of ORC pump and expander.

In conclusion, ORC systems connected to PVT collectors have potential as alternative heat-to-power conversion systems. However, currently, only limited experimental data is available on this type of system, especially under transcritical operating conditions. Investigations have mainly focused on the subcritical operation and only few experimental measurements under transcritical conditions have been performed. Therefore, in this work experimental data of a small-scale transcritical ORC connected to concentrating thermal collectors are presented and discussed. The measurement campaign has focused specifically on evaluating the performance of the system under transcritical operating conditions. The paper is structured as follows. First, the experimental test rig is described, as well as the executed experimental campaign and the most important performance indicators are highlighted. Second, the results on the overall performance of the system are discussed. Next, a closer look is taken at the performance of the scroll expander.

2. DESCRIPTION OF THE TEST RIG AND EXPERIMENTAL MEASUREMENT CAMPAIGN

2.1 Transcritical ORC connected to concentrating thermal collectors

The small-scale transcritical ORC is located in Athens, Greece (37°59'09"N, 23°42'21"E). A schematic of the installation is given in Fig 1. This test rig has been discussed extensively in previous works (Kosmadakis *et al.*, 2016a; Kosmadakis *et al.*, 2016b; Golonis *et al.*, 2021), so therefore only the most important aspects for the current investigation are highlighted. The ORC has a nominal electrical capacity of 3 kWel and is charged with R404a (T_c: 345.3 K (72.2°C), p_c: 3.73 MPa). The electric heater installed in the water circuit, which serves as a backup for when the solar irradiation is insufficient to reach test conditions, has a total capacity of 48 kWel. The refrigerant pump is a triplex diaphragm pump, the expander a scroll type one (a modified commercial scroll compressor with a built-in volume ratio of 2.8 and a swept volume of 127.1 cm^3). Both the pump and expander rotational speed are regulated with frequency inverters. The supercritical heat exchanger has been developed for this mode of operation specifically and is of the helical coil type with a capacity of 41 kW. Refrigerant flows upwards in the coil placed in an annulus, while the heat transfer fluid flows downwards in the annulus. The condenser is an evaporative condenser. When the ORC is not operating, an air chiller dissipates the heat from the collectors.

The installed solar field, consisting of 10 collectors, has a total nominal peak electric capacity of 10 kWp and nominal heat capacity of 41 kWth. The collectors are equipped with a single-axis solar tracking system and rotate horizontally about an East-West tracking axis. Water is used as the heat transfer fluid in the circuit connected to the solar collectors.

Measurement equipment, including temperature and pressure sensors and two pyranometers to measure the total and diffuse irradiance, is installed as well. Temperatures were measured with an accuracy of 0.1 K and pressures with 0.35 or 0.6 bar, depending on whether they are installed on the low pressure or high pressure side, respectively. The pyranometers have an accuracy of 2%. The volume flow rate of the water in the solar collectors' circuit was measured with an ultrasonic flow meter (with an accuracy of 1%). The volume flow rate of the refrigerant was calculated using the pump's characteristic (linear correlation between volume flow rate and speed) and the accuracy is estimated at 2% (Kosmadakis *et al.*,2016a). The power consumed by the ORC pump and generated by the expander was measured with an accuracy of 0.05 kW.

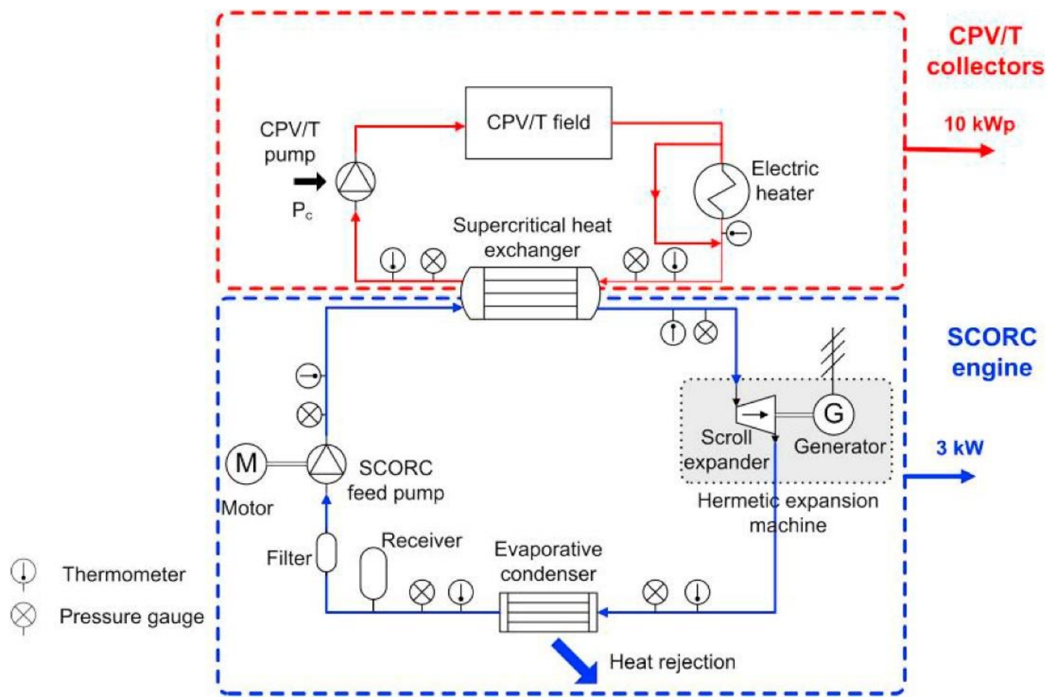


Figure 1: Schematic diagram of the transcritical ORC test rig (Kosmadakis *et al.,* 2016a).

2.2 Experimental campaign

In order to reach transcritical conditions (i.e. both temperature and pressure at the outlet of the supercritical heat exchanger on the refrigerant side above its critical values), measurements were performed on clear and sunny days spread over July, August and September 2021. Solar irradiation under these conditions was maximum. Start-up of the total system was as follows. First, the pressure of the water in the solar collector's circuit was checked and raised if necessary (up to a pressure of around 3 bar). Second, the flow path of the water to the air-chiller was closed off by a set of valves and the evaporative cooler was turned on. The frequency of the water pump was set to 50 Hz. Next, the solar collectors were powered, meaning the solar tracking system was activated and the water in the circuit could be preheated. When the water reached a temperature between 60 to 65°C, the ORC was started. The ORC pump first ran at a low frequency of 10 Hz. Gradually, pressure and temperature in the system increased and pump frequency was increased in a stepwise manner. When the pump frequency was at 20 Hz, the expander was put into operation as well, with a start-up frequency of 10 Hz. The maximum solar irradiation that could be obtained was around 1,000 W/m^2. Under these conditions, supercritical pressures could be obtained (for high ORC pump speed and low expander speed), but the temperature at the inlet of the expander remained below the critical value. Therefore, the back-up electrical heater was employed almost constantly during the measurements described in the following.

A total of 43 (quasi) steady-state operating points were measured during the experimental campaign, of which 39 were performed under transcritical operating conditions. Post-processing of the measurements was done with the EES software. Validation of the test rig and measurements is done by calculation of several energy balances, defined in equations (1) and (2). In these equations, $\dot{Q}_{hx,col}$ is the heat transferred to the ORC in the supercritical heat exchanger on the collectors' side. $\dot{Q}_{hx,ORC}$ is the heat transferred to the ORC in the supercritical heat exchanger and $\dot{Q}_{cond,ORC}$ is the heat rejected in the condenser, both calculated on the refrigerant side. $\dot{W}_{exp}$ is the power generated by the expander and $\dot{W}_p$ the power consumed by the ORC pump.

$$dE_{ORC,rel} = \frac{\dot{Q}_{hx,ORC}+\dot{W}_{pp}-\dot{W}_{exp}-\dot{Q}_{cond,ORC}}{\dot{Q}_{hx,ORC}} \tag{1}$$

$$dE_{hx,rel} = \frac{\dot{Q}_{hx,col}-\dot{Q}_{hx,ORC}}{\frac{\dot{Q}_{hx,col}+\dot{Q}_{hx,ORC}}{2}} \tag{2}$$

First of all, the error on the energy balance over the ORC itself was calculated (equation (1)). The maximum absolute error on the energy balance was 16.7%. However, on average the absolute error was only 2.8%. As a second validation, the error on the heat balance over the supercritical heat exchanger has been calculated as well (equation (2)). On average, the heat balance only closed within 23.2%. These large deviations in heat balance can be explained by the high heat losses that occur in the heat exchanger. The maximum heat losses that occurred were in the range of 22 kWth. This issue was already highlighted in a previous paper (Golonis *et al.*, 2021) and is due to the large uninsulated surface of the supercritical heat exchanger.

2.3 Performance indicators

Several performance indicators exist, both to represent the efficiency of the CPVT field, ORC unit and separate components. The indicators illustrated in Section 3 will be shortly explained here. However, for the full elaboration, we refer to Golonis *et al.* (2021).

The thermal efficiency $\eta_{th,col}$ of the collectors is defined as:

$$\eta_{th,col} = \frac{\dot{Q}_{col}}{A_{col} * G_{b,n}} \tag{3}$$

In equation (1), $\dot{Q}_{col}$ represents the heat generated by the thermal collectors, A_{col} is the total collector area and $G_{b,n}$ is the direct normal solar irradiance.

Efficiency of the ORC unit can be expressed through its thermal efficiency $\eta_{th,ORC}$:

$$\eta_{th,ORC} = \frac{\dot{W}_{net}}{\dot{Q}_{hx,ORC}} = \frac{\dot{W}_{exp}-\dot{W}_{pp}}{\dot{Q}_{hx,ORC}} \tag{4}$$

Here, $\dot{W}_{net}$ represents the net power production of the ORC unit.

For the ORC pump and expander, an isentropic efficiency, $\eta_{s,pp}$ and $\eta_{s,exp}$ respectively, can be defined:

$$\eta_{s,pp} = \frac{\dot{m}_{ORC} * (h_{pp,out,s}-h_{pp,in})}{\dot{W}_{pp}} \tag{5}$$

$$\eta_{s,exp} = \frac{\dot{W}_{exp}}{\dot{m}_{ORC}*(h_{exp,in}-h_{exp,out,s})} \tag{6}$$

$h_{pp,in}$ and $h_{exp,in}$ are the specific enthalpies at the pump and expander inlet, $h_{pp,out,s}$ and $h_{exp,out,s}$ are the enthalpies at the outlet if the processes would occur isentropically.

The pressure ratio (PR) over the expander is defined as:

$$PR = \frac{p_{exp,in}}{p_{exp,out}} \tag{7}$$

3. RESULTS AND DISCUSSION

3.1 Evaluation of the overall performance of the total system

First, the performance of the collectors is evaluated. In Figure 2, the collectors' thermal efficiency is plotted in function of the direct normal solar irradiance. The figure shows that for an increase in direct normal solar irradiance, the efficiency of the collectors increases as well. However, also an upper limit to this positive influence is seen (with a maximum efficiency of 57.2%). When reaching irradiation levels between 800 to 1000 W/m^2, no noticeable further efficiency improvement is achieved. Similar behavior of the efficiency in function of diffuse or total irradiance is found. However, for the diffuse irradiance the range is much smaller as this parameter only varies from approximately 55 to 85 W/m^2 for the measurements considered in this work.

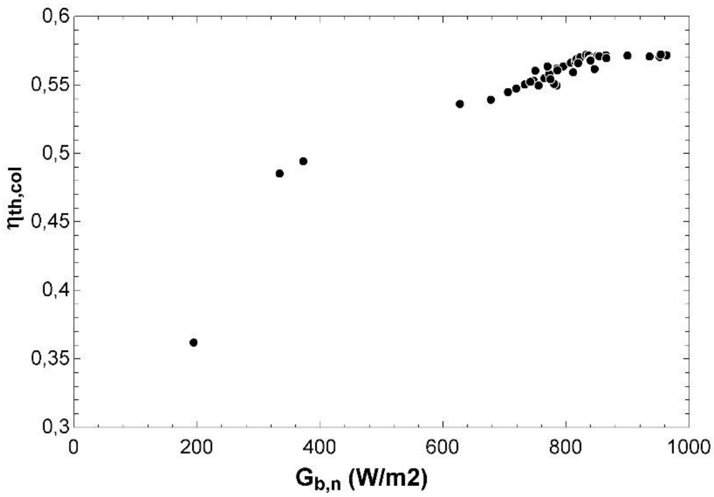
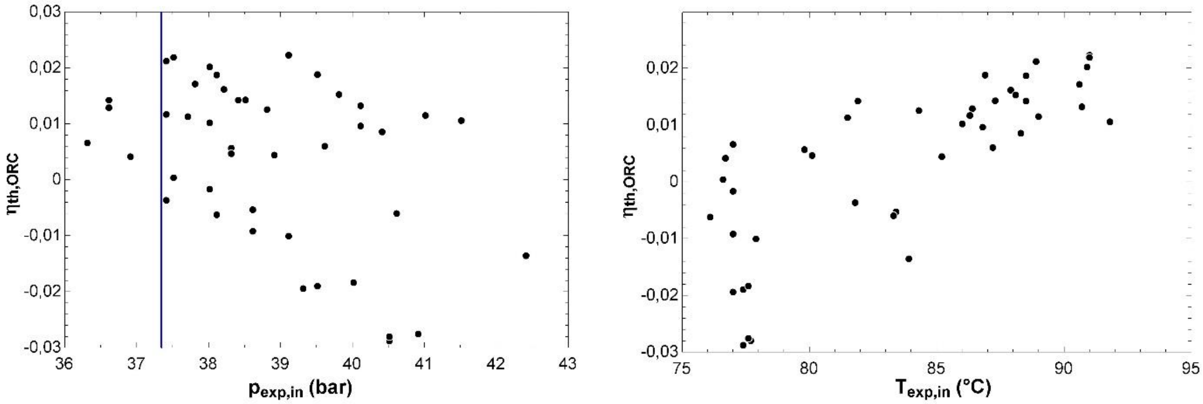


Figure 2: Thermal collector efficiency in function of direct normal solar irradiance.

In Figure 3, the thermal efficiency of the ORC unit is displayed in function of expander inlet pressure and temperature. The straight line in the left graph represents the critical pressure of the refrigerant. As all displayed measurements have an expander inlet temperature that is above the critical temperature of R404a, this line of critical temperature is not visible on the right graph. Based on these graphs, it can be concluded that the efficiency of the ORC unit is not so much influenced by the pressure at the inlet of the expander, but more by the temperature that can be reached in that location. An increase in expander inlet temperature mainly results in an increase in thermal efficiency. Overall, the efficiency values are low compared to normal subcritical operation (max. of only 2.2%) and even values below zero were measured. This means that the power consumed by the pump to reach the high pressures exceeded the power generated by the expander. This is due to the poor expander part-load performance and high pump power consumption under the current measurement conditions, as will be explained in more detail in section 3.2. The strong correlation between overall ORC performance and expander conditions is also illustrated in Figure 4, depicting ORC efficiency in function of expander rotational speed (for a constant pump frequency of 60 Hz).



(a) (b)

Figure 3: ORC thermal efficiency in function of expander inlet pressure (a) and temperature (b).

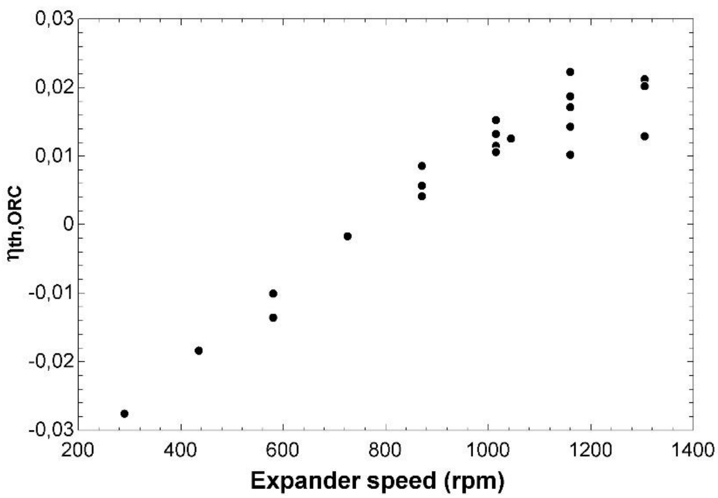


Figure 4: ORC thermal efficiency in function of expander rotational speed at a constant pump frequency of 60 Hz.

An important operational parameter of an ORC is the pressure ratio over the expander. Therefore, Figure 5 shows the variation of the ORC efficiency in function of the pressure ratio. Overall, a downward trend is observed, with a maximum close to a PR of 2. This ideal pressure ratio is strongly related to the built-in volume ratio of the modified air scroll compressor. When the pressure ratio over the expander is below or above this ideal ratio, additional losses related to over- and under-expansion, respectively, occur. Under the current measurement conditions, under-expansion losses will thus mostly be taking place in the expander. In addition, the performance of the expander may also be affected because of increased leakage flow rates with increasing pressure ratio.

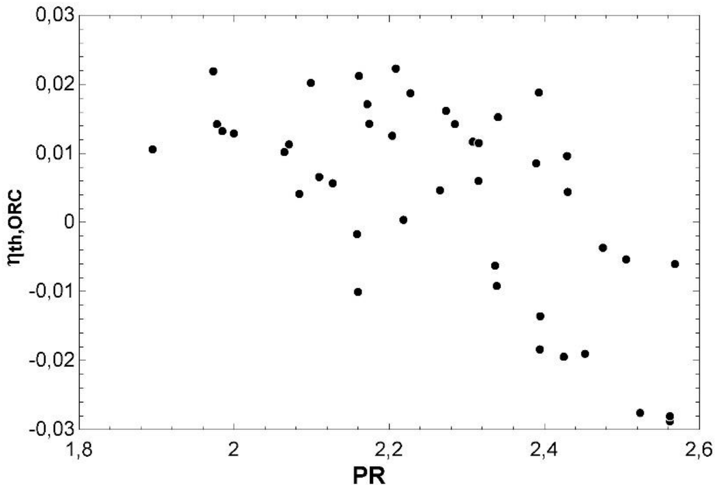


Figure 5: ORC thermal efficiency in function of pressure ratio over the expander.

3.2 Evaluation of the expander and pump's performance

In this section, a closer look will be taken at the operation of the expander and pump, in order to explain the low thermal efficiencies of the ORC unit under the current measurement conditions. Figure 6 displays the power of the pump, the power generated by the expander and the net power produced by the ORC unit in function of the expander rotational speed. The power used by the pump is independent of the expander rotational speed (and accordingly independent from pressure ratio as well). However, the power generated by the expander is strongly dependent on expander speed, with high expander speeds corresponding to higher power generation (and consequently higher net power production). In Figure 7, pump and expander isentropic efficiency are presented in function of expander rotational speed. An increase in expander speed results in an increase in expander isentropic efficiency, but the values overall are rather low. The pump isentropic efficiency has the opposite trend and the values are significantly higher (they do not drop below 53%).

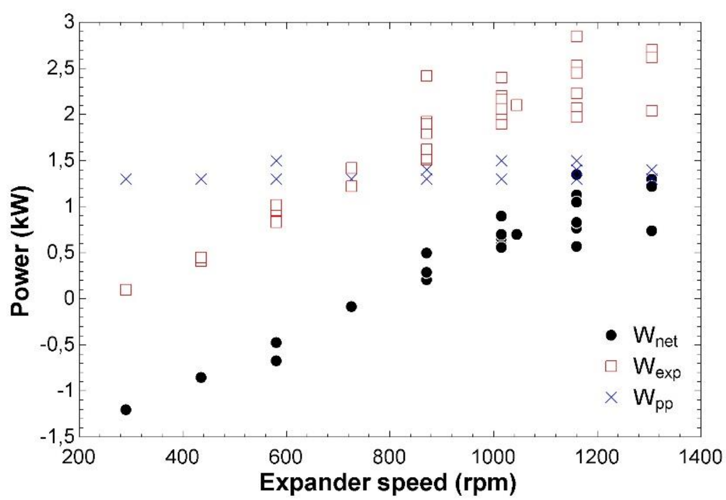


Figure 6: Power generated by expander, power used by pump and net power production in function of expander rotational speed at a constant pump frequency of 60 Hz.

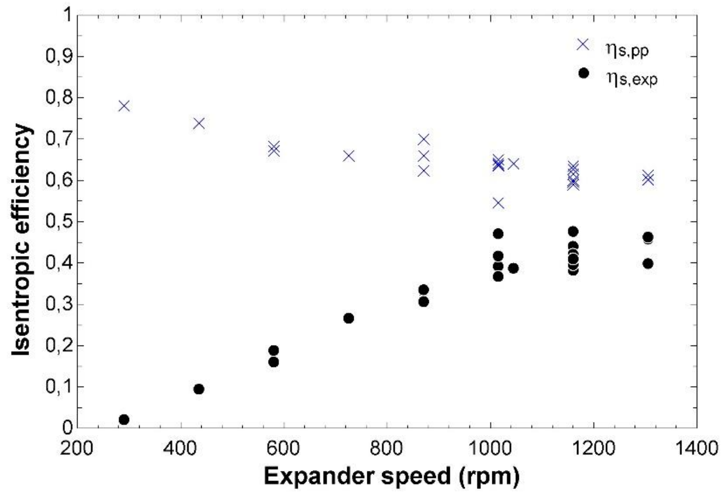


Figure 7: Isentropic efficiency of pump and expander in function of expander rotational speed at a constant pump frequency of 60 Hz.

Based on the results presented here, it can be concluded that under the current measurement conditions, the ORC unit operates inefficiently. However, the maximum thermal efficiency of 2.2% that was measured under transcritical conditions is in line with or better than values previously reported in literature. Landelle *et al.* (2017) reported thermal efficiencies of only 1%. Hsieh *et al.* (2017) measured thermal efficiencies between 2.63 – 2.75% (depending on the heat source temperature). On the test rig considered in the current work, Kosmadakis *et al.* (2016b) measured values up to 4.4% under lab testing conditions, while for the field tests (i.e. ORC coupled to CPVT field) reported by Kosmadakis *et al.* (2016a) values below 1% were measured.

The main influencing factor on the low performance of the unit is the low operating efficiency of the expander. In order to reach supercritical conditions at the expander inlet, the maximum expander rotational speed that could be applied was only 22.5 Hz (only half of the nominal rotational speed). However, as indicated by the graphs, the expander performance is lower at low rotational speeds. This leads to the conclusion that the scroll expander implemented in the current setup is not properly sized for operating the unit at transcritical conditions. In addition to the expander performance, the low thermal efficiency of the cycle is also due to the high power consumption of the pump under transcritical conditions. This leads to a very high back work ratio, negatively influencing the overall performance of the unit.

The main goal of this work is to investigate the initial challenges of a proof-of-concept transcritical organic Rankine cycle coupled to CPVT collectors. Even though the reported thermal efficiencies of the ORC unit are low, the overall system combining the thermal collectors with the ORC unit shows promising results. In order to become competitive with or surpass the performance of the subcritical cycle system, the current unit should approximate ORC thermal efficiencies of around 5% (Golonis *et al.*, 2021). Reaching this efficiency also means a second law efficiency of more than 50% (i.e. exceeding half of the Carnot efficiency) under the current measurement conditions, indicating a good ORC engine according to Tchanche *et al.* (2014). Future work includes performing measurements under transcritical operating conditions, but for higher expander rotational speeds (22.5 – 50 Hz). This way, the performance of the system can be evaluated fairly compared to subcritical operating conditions as the losses in the expander should be reduced significantly under these conditions. For this purpose, it might be necessary to install another (smaller) expander onto the current test rig in order to operate the expander closer to its nominal operating conditions. In addition, the performance of the supercritical heat exchanger will be investigated as well. This heat exchanger was custom-built for this application specifically (Lazova *et al.*, 2016; Lazova *et al.*, 2017). Based on the measurements, insight can be given into its design calculations. This allows for optimization of the supercritical heat exchanger design, facilitating improved ORC performance and future system designs.

4. CONCLUSIONS

Operating an organic Rankine cycle under transcritical conditions can theoretically improve the performance of such a system as losses during heat transfer to the refrigerant can be reduced and cooling of the heat source can be increased. In literature, mainly analytical studies have been performed. However, experimental validation is key in order to assess such a system under practical conditions and evaluate the performance and efficiency. In addition, solar energy has huge potential as a renewable energy source, but ORC applications are scarce. Therefore, this work discusses the performance of a transcritical ORC connected to CPVT collectors. Measurements are performed under transcritical operating conditions and several performance indicators are evaluated. The maximum thermal collector efficiency that is obtained is 57.2%. This efficiency increases for an increase in solar irradiation, however reaching a certain limit. Overall, the thermal efficiencies of the ORC unit are rather low compared to normal subcritical operation, with 2.2% as a maximum. These low values are mostly because of the low part-load performance of the current scroll expander installed on the test rig. In addition, the power of the pump to reach supercritical pressures is also rather high, negatively impacting efficiency. Thermal efficiencies are highly dependent on expander rotational speed, with an increase in efficiency for an increase in expander speed. Pump power consumption stays rather constant, but the power generated by the expander rises in function of expander rotational speed. Even though the thermal efficiencies reached under the current measurement conditions are quite low, they are in line with values previously reported in literature. In order to create a full picture of the performance of the TORC-CPVT collector system, future work should include measurements performed at higher expander rotational speeds. In addition, the performance of the current supercritical heat exchanger will be evaluated based on the current measurements.

NOMENCLATURE

A	area	(m^2)
dE	error on energy balance	(/)
G	solar irradiance	(W/m^2)
h	specific enthalpy	(J/kg)
$\dot{m}$	mass flow rate	(kg/s)
T	temperature	(K)
p	pressure	(Pa)
$\dot{Q}$	heat transfer rate	(W)
$\dot{W}$	power	(W)

Special characters

η	efficiency	(/)

Subscript

b	direct
c	critical
col	collector
cond	condenser
el	electric
exp	expander
hx	heat exchanger
in	inlet
n	normal
net	netto
out	outlet
p	peak
pp	pump
rel	relative
s	isentropic
th	thermal

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