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(coordinadores)

Proceedings of the 7th International Seminar on ORC Power Systems

Editorial Universidad de Sevilla

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(ORC2023)

4th to 6th
SEPTEMBER
SEVILLE 2023

EDITORIAL
UNIVERSIDAD DE SEVILLA

Sevilla, 2024

Colección Actas
Núm.: 91

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ISBN 978-84-472-2745-7
DOI: https://dx.doi.org/10.12795/9788447227457

Diseño de cubierta y maquetación: los autores

INDEX OF CONTRIBUTIONS

DOI: https://dx.doi.org/10.12795/9788447227457_83

On the plant improvement of Solar-driven ORC-based power unit for domestic micro-cogeneration

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ABSTRACT

The integration of flat solar thermal collectors and ORC-based power units ensures the simultaneous production of heat and electric power in domestic applications (CHP). Thus, such micro-cogenerative solutions ensure to reduce the use of fossil fuels and CO_2 in a sector that accounted for about 30% of global energy-related CO_2 emissions in 2021, considering both residential and commercial buildings. The significant variability of solar power during the day and domestic hot water (DHW) demand pushes the unit to work in off-design and transient conditions frequently. Therefore, to maximize the energy recovery of the unit, the design phase and the components selection assume a crucial role. The critical component is the expander and, generally, volumetric machines are adopted for their operating flexibility and robustness when working with highly variable hot sources. Among the volumetric expanders adopted for this kind of application, scroll machines present higher performance and reliability than other positive displacement technologies. Nevertheless, similarly to the other volumetric expanders, such devices still have room for improvement. Indeed, in many applications, they are obtained by reversing scroll compressors. Hence, to participate in the improvement of these machines, a comprehensive model was developed following an integrated zero and mono-dimensional (0-1D) thermo-fluid-dynamic approach. The model was validated through experimental data measures during a comprehensive testing campaign performed on a fully instrumented solar-driven ORC-based power unit which employs a 1 kW scroll expander as mechanical power at design. Once the scroll expander model was validated, it was theoretically optimized in terms of working fluid flow rate aspiration (volumetric efficiency), indicated performances and mechanical power produced. Subsequently, the benefits of the optimized machine to the recovery unit performances have been estimated.

1 INTRODUCTION

Among the various sources of renewable energy existing – wind, tidal, and geothermal energy (Ardeh *et al.*, 2019) – solar energy is one of the most promising because it is available in large quantities and can be converted easily into electric or thermal energy (H. Chen *et al.*, 2022). On the other hand, solar energy fluctuates and becomes intermittent and very diffuse, so a proper thermal storage system is required (Altayib and Dincer, 2022), and solar-driven systems have higher costs and lower efficiency compared to conventional plants (Algieri *et al.*, 2022). Solar radiation can be converted directly into electricity using photovoltaic technology or thermal energy through solar thermal collectors (Y. Chen et al., 2022). In the second case, the heat obtained from solar radiation is transformed into electric power in downstream recovery units based on an Organic Rankine Cycle - ORC- (Gupta *et al.*, 2022), a conversion cycle suitable from medium-low grade temperature heat sources (Alvi *et al.*, 2020). Solar-ORC-based plants employed as cogeneration units are a promising solution for reducing GHG emissions in the residential sector since they can meet both the needs for electricity and domestic hot water (Jaubert *et al.*, 2021; Bagherian and Mehranzamir, 2020); Martinez *et al.*, 2021). Solar ORC units allow for reducing losses associated with energy transport and distribution (Pereira *et al.*, 2018), but their economic convenience depends on the scenario in which they operate (Arteconi *et al.*, 2019). The most common layout modification consists of changing the basic cycle architecture by inserting a recovery heat exchanger after the pressurization of the working fluid fed by when it leaves the expander to increase the cycle efficiency. Ochoa *et al.* (2022) compared the performance of two different configurations (base and regenerative) from energy, exergy, and thermo- economic perspective, considering the average solar radiation data of six areas and concluding that the regenerative configuration is not convenient under the examined operating conditions. A thermal recovery before the main one prevents part of the primary recovery inside the Heat Recovery Steam Generator (HRSG), reducing the hot source exploitation. Javed and Tiwari (2023) carried out a comparative analysis of the energy and economic performances of three layouts (base, recuperative and regenerative) for four different working fluids. The best performances are obtained through the recuperative configuration with a power increase of +36.6% compared to the basic layout; A similar result is also assessed by Nondy *et al.* (2021), who found that the layout with the best performance is the recuperative-regenerative one, which shows net power and exergy efficiency 16.19% and 15.33% higher than the basic configuration. Concerning the components, the expander behavior affects the plant's performance and cost-effectiveness (Imran *et al.*, 2016). Scroll expander is one of the most adopted machines thanks to its reliability and high efficiency. Zhang *et al.* (2023) conducted experiments on an ORC-based recovery unit using three scroll expanders (two hermetic and one open-drive) with different built-in volume ratios. Ziviani *et al.* (2018) integrated an open-drive and oil-free scroll expander into an ORC-based plant. The low maturity level of the scroll expander technology requires design and technological improvements supported by theoretical and experimental studies. In fact, basic studies can be supported by models, but real performances necessarily require experimental data (Fatigati *et al.*, 2022a, Kolasinski *et al.*, 2017). This paper proposes a thermo-fluid-dynamic model of a scroll expander developed with a mono and zero-dimensional approach subsequently validated with experimental data on a test bench in which an ORC-based solar-driven recovery unit is operated. The model of the expander was modified to consider the effects of geometrical modifications to improve volumetric, indicated and mechanical efficiencies. The effects on the performances of the whole ORC-based solar-driven recovery unit have been investigated.

2 MATERIALS AND METHODS

The test bench developed in Fatigati *et al.* (2022a) was adopted to provide the experimental characterization of the ORC-based power unit. The ORC-based power unit (Figure 1) was built to be integrated with 15 m^2 of flat plate solar thermal collectors mounted on a rooftop located in central Italy. The rated power of the unit is 500 W. The solar power is simulated through the modulation of two electric resistances of 12 kW each (a), heating the hot water (HW) stored in a 135 L tank pressurized with air to avoid its evaporation (b). In this way, modulating the heat delivered by the electrical resistances, the effect of the solar source was simulated. Hot water is circulated by a dedicated electric motor-driven pump (c), and its mass flow rate is regulated through a valve (d) to reproduce the variations in the thermal load on the evaporator caused by the fluctuating availability of solar radiation. In the plate heat exchanger Heat Recovery Vapor Generator (HRVG) (e), the hot water heats the working fluid (WF) (R245fa), which enters a scroll expander (Figure 2) (f) as a superheated vapor. The lubrication was provided with an ISOVG 68 POE oil mixed with the working fluid (R245fa). The amount of oil was set at 5 % of the total charge (3kg). The mechanical power produced by the expander is converted into electrical power through a generator and dissipated on a rheostat-adjustable electric load (g). Hence, the rotation speed of the scroll expander is not externally imposed, but it is defined by the dynamic equilibrium of the positive torque produced by the expander and of the negative torque produced by the electric generator, which feeds a variable electric load. In other words, being the electrical generator not connected to the grid, the speed of rotation cannot be actively controlled. It was observed as it grows linearly with the mass flow rate, thus helping keep the expander pressure ratio close to the design value. The plant adopts a recuperative configuration, according to previous literature results showing the potential benefits of this configuration (Nondy *et al.,* 2021). The working fluid enters the internal heat exchanger after evolving in the expander (h) and before entering the condenser (i). This way, the working fluid exiting the pump is pre-heated before entering the HRVG, increasing the unit efficiency and reducing the thermal load in the condenser. In the condenser, fed by tap water on the cold side, the working fluid is brought back into a subcooled liquid state and then gathered by a 3 L tank (l) working as a fluctuation damper. It also behaves as a working fluid reservoir when a sudden flow rate increase is requested by the pump, avoiding a potential lack of fluid at the pump intake. The working fluid is finally recirculated by a diaphragm pump with a 6.3 cm3 volume displacement (m), driven by an asynchronous electric motor with an inverter that allows the flow rate to be adjusted according to the operating requirements of the system. The instrumentation includes temperature and pressure sensors upstream and downstream of each component (n), a Coriolis (o) and two magnetic flowmeters (p) for reading respectively the flow rates of working fluid and water at the evaporator and condenser, a wattmeter for measuring the expander and pump power (q), and an optical probe inside the scroll casing that provides the measurement of the rotational speed and transmits the signal to an oscilloscope. The experimental data allows the validation of a dedicated expander model. Subsequently, an operating map was provided by the expander model and introduced inside a comprehensive model of the whole ORC-based power unit. The scroll theoretical model was obtained by updating the one developed by the authors in Fatigati *et al.* (2022b) for the application at hand. The considered scroll is reported in Figure 2, where the fixed (a) and orbiting (b) scroll can be observed. The fixed and orbiting scrolls define six chambers (Figure 3). During the intake phase, the machine chambers are in 1a and 1b positions and they are axially filled. The intake phase ends after a complete rotation of the shaft. After the intake phase, the chambers branch off and are in positions 2a and 2b. As the expansion continues, the chambers proceed toward positions 3a and 3b in correspondence to which the discharge phase occurs. Therefore, such behavior suggests a symmetric structure for the model, where the chambers are symmetrically represented, reproducing the chamber expansion from position 1 to 3.

Figure 1: Solar ORC-based power unit

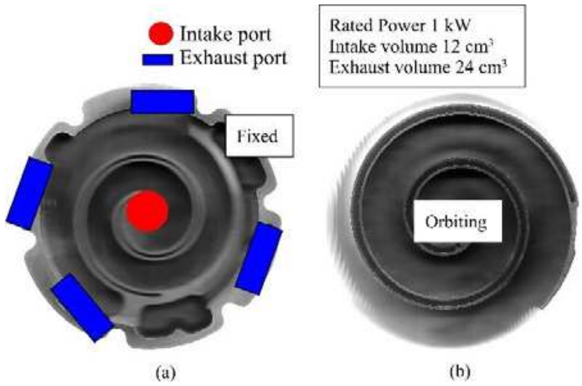

Figure 2: Scroll geometrical model

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The model of the scroll was developed in the GT-Suite™ environment following an integrated mono (1D) and zero (0D) thermo-fluid-dynamic approach. The 1D approach was adopted to represent the dynamic phenomena taking place in the connecting pipes during the intake and discharge phases. The intake and discharge pipes were discretized and the Navier-Stokes Equations were solved through an explicit integration method for each subsystem. Concerning the 0-D analysis, it was used to represent the volumetric losses modeled through the Poiseuille-Couette equations and mainly caused by flank and radial leakages represented in Figure 3 as RL and FL components. Leakages not only affect the volumetric efficiency but play a significant effect also from an energetic point of view. Indeed, they influence the trend of the pressure inside the chamber as a function of its volume over time, i.e., the indicated power. The net power delivered by the expander can be determined by subtracting the mechanical losses due to friction from the indicated power. Concerning the model of the mechanical losses, it was considered according to a map of the mechanical efficiency following the approach of Fatigati et al. (2022b). Once validated, the expander model was used as a software platform to optimize its performance. Subsequently, an operating map can be provided for a wide operating range and introduced in the comprehensive model of the ORC-based power unit developed following the approach of Marchionni et al. (2022). Compared to the cited model, the main novelty is the introduction of a recuperative stage. Moreover, the present recovery unit presents a lower size than the one just cited, which was designed to recover thermal energy from the exhaust gases of an Internal Combustion Engine. The model of the ORC-based power plant developed here is reported in Figure 4. The pump (a) was modeled through a look-up table preliminary derived for simplicity. The recuperator (b), the Heat Recovery Vapor Generator (HRVG) (c), and the condenser (e) can be modeled through physical models which consider the geometry of the heat exchangers and the different heat transfer coefficients during different heat exchanges. The correlations of Dittus and Boelter (1985) are used for the single-phase and supercritical case as it is recommended for turbulent flow in smooth pipes for heating or cooling application. For the two-phase case, the correlation developed by Yan et al. (1999) was used for the condensation, whereas the evaporation was represented through the correlation developed by Kandlikar (1990). These correlations are recommended for the plate heat exchanger to represent the two-phase condensation and evaporation, respectively. Through element (f), the 3 L plenum upstream of the pump can be modeled, while element (n) allows considering the working fluid mass charge and the initial conditions. The flow rate of the hot water of the reservoir (set by the pump speed (g)) and its temperature were input data (h) at the HRVG from one side. Knowing the working fluid flow rate and its inlet temperature at the other side of the HRVG, the conditions of the two fluids at their respective outlets can be calculated, as well as the thermal power absorbed by the ORC-based recovery unit. At the condenser side, the temperature of the tap water sets the condensation pressure of the working fluid. Flow rate and tap temperature (m) entering the condenser fix the conditions at one side of the condenser, while the flow rate of the working fluid and its temperature (from the expander outlet) fix the conditions at the other side. It is worth noting that for the considered plant architecture, the expander speed is not externally imposed but depends on the equilibrium realized on the shaft. A linear dependence of the speed (ranging from 4073 RPM up to 5458 RPM) with the working fluid mass flow rate and, consequently, the pump speed was observed and implemented inside the model. Although the model was used for steady-state analysis in this work, it can also be used to evaluate the transient behavior of the unit.

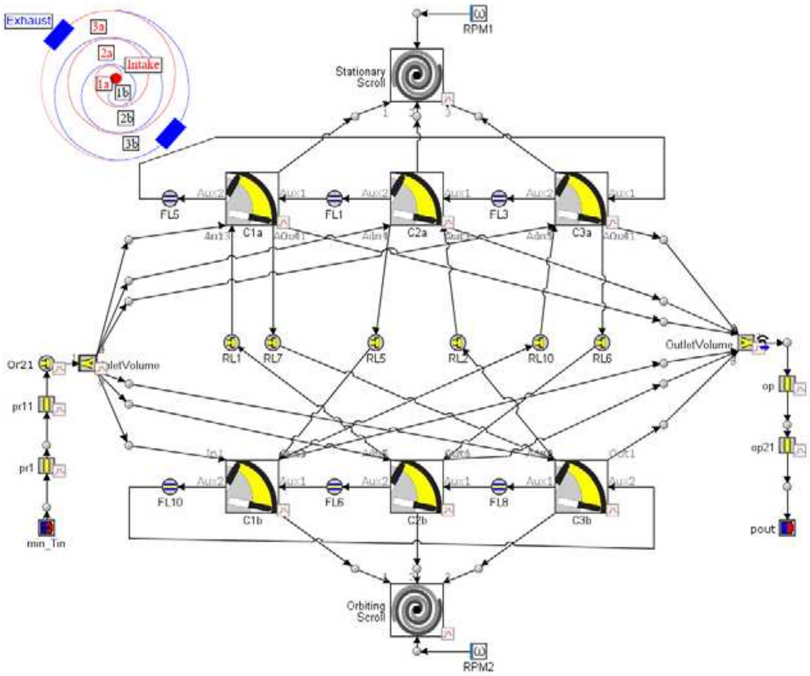

Figure 3: GT-Suite scroll numerical model

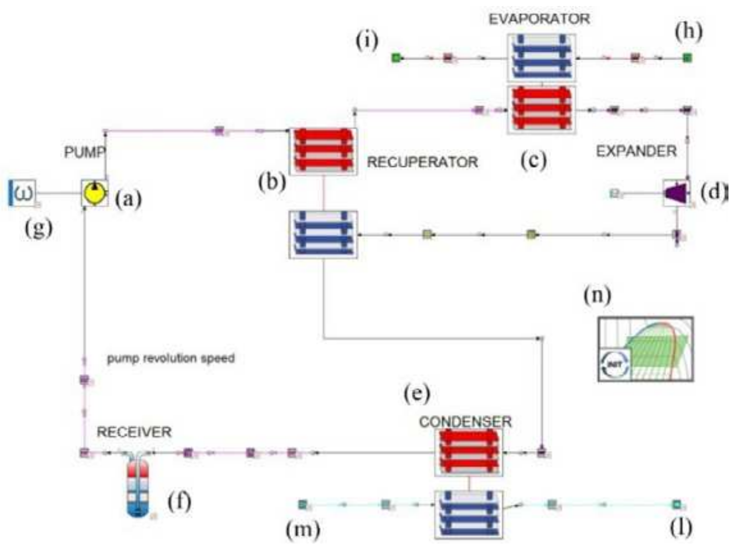

Figure 4: ORC-based power unit model

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Thanks to the broad experimental data set, expander and ORC unit models were validated to demonstrate their accuracy. A satisfactory agreement was obtained by comparing the theoretical results of the expander model with the experimental data reported in Table 1. In particular, the Root Mean Square Errors (RMSE) in terms of expander intake pressure, power and efficiency are equal to 4%, 2 % and 4% respectively. The model also presents a good prediction regarding the discharge temperature of the working fluid with an average absolute error of -2 K. Therefore, the model reproduces the real expander behavior. Once validated, an operating map was developed and introduced inside the ORC-based recovery unit software platform. The accurate model of the expander contributes to a good prediction of the performances of the whole recovery unit. Indeed, in Table 2, the differences between theoretical and experimental data are reported. Concerning the working fluid mass flow rate, the maximum error was equal to -1.8%, whereas for maximum and minimum pressures, maximum errors were equal to -2.7% and 10.5%, respectively. It is worth noticing that maximum pressure and temperature were measured at the evaporator outlet, whereas minimum pressure and temperature were at the pump inlet. Regarding the greatest and lowest temperatures, the maximum errors were equal to -5 K and 9.6 K, respectively. The maximum errors on the hot side inlet and outlet temperatures at the regenerator are equal to 5.7 K and 4.5 K. On the other hand, the cold side outlet temperature differs by 6.1 K from the experimental value. Maximum deviations between modeling and experimental results of power and efficiency of the recovery unit are -14.7 % and 10.7%, respectively. Hence, the model accuracy can be considered satisfactory given the wide operating range analyzed. Indeed, the 6 points chosen represent a significant variation in the mass flow rate of the working fluid (from 17 g/s up to 50 g/s) compared to the design value (40 g/s). Indeed, in Marchionni et al. (2022), the proposed model approach accurately reproduces an ORC-based unit with more extended operating conditions.

Table 1: Experimental quantities

Experimental quantities	**Units**	**1**	**2**	**3**	**4**	**5**	**6**
mass flow rate	g/s	50.7	45.9	41.4	49.3	17.8	23.0
Maximum pressure	bar	10.4	9.7	9.0	10.1	5.0	5.9
Maximum temperature	K	381	377	379	377	365	364
Minimum pressure	bar	1.5	1.5	1.4	1.5	1.2	1.3
Minimum temperature	K	293	293	291	296	288	287
Expander speed	RPM	5458	5256	5066	5399	4073	4292
Expander power	W	583	565	546	563	271	347
Expander efficiency	%	39	42	45	40	58	55
Power	W	360	386	404	354	256	314

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Table 2: Errors between experimental and theoretical data

errors	**1**	**2**	**3**	**4**	**5**	**6**
mass flow rate [%]	-1.0	-0.9	-1.3	-0.4	-1.6	-1.8
ORC maximum pressure [%]	-1.9	-0.1	-0.2	-2.7	-2.1	-1.8
ORC maximum temperature [K]	-1.6	2.5	1.6	-5.0	0.8	0.7
ORC minimum pressure [%]	1.5	-1.2	0.6	-4.9	9.3	10.5
ORC minimum temperature [K]	5.3	4.5	6.6	2.1	8.2	9.6
Expander electrical power [%]	-0.6	-1.3	-1.1	-0.4	-10.8	-7.6
Expander efficiency [%]	1.1	1.4	1.0	0.6	11.9	2.8
ORC unit electrical power [%]	-5.4	-3.8	-10.0	-11.7	-12.7	-14.7
ORC efficiency [%]	4.4	2.5	9.2	11.4	9.0	10.7

3 RESULTS

Once verified the effectiveness of the model for both the expander and the whole recovery unit, it has been used as a software platform to assess the impact of some expander technological improvements on the recovery unit performances. Hence, the first step was to analyze the improvement on the expander produced by different clearance flank gap values ranging from 10 to 30 μm, being 20 μm the value considered as a reference. The performance of the ORC unit in a wide range of operating conditions was assessed through the model. The variation of ORC unit power and performance as a function of the working fluid mass flow rate and the hot water temperature inside the tank is reported. The hot water inside the tank represents the hot source of the recovery unit; it feeds the Heat Recovery Vapor Generator favoring the vaporization and the superheating of the working fluid. The analysis refers to a fixed hot water flow rate of 8 L/min. As Figure 5 reports, the reduction of the clearance gaps provides an improvement in the machine performance according to the expectations. Indeed, it can be seen how the power produced by the expander grows as the clearance gap decreases. Considering, for instance, the case in which the mass flow rate is equal to 70 g/s, the power grows from 853 W up to 985 W reducing the clearance from 30 μm to 10 μm. This reduction can be achieved from a technological point of view and the effect on power produced is significant (+15% power increase). Such improvement is due to the increase in volumetric efficiency, which is the ratio between the theoretical working fluid mass flow rate entering the chambers and the measured one.

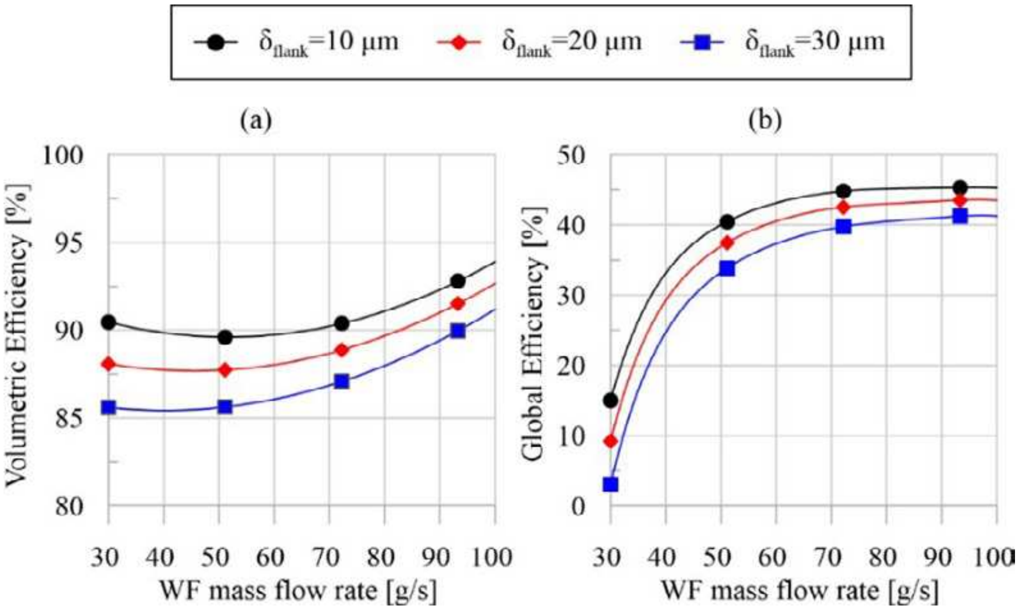

Figure 5: Expander volumetric (a) and global efficiency (a) as a function of WF mass flow rate for different values of clearance flank gap.

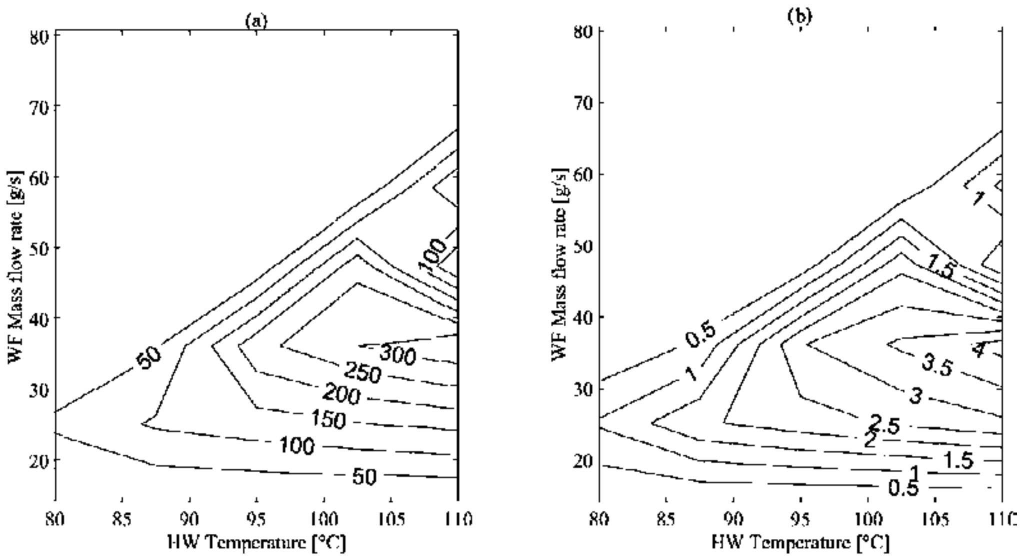

Figure 6: Iso-power [W] (a) and efficiency [%] (b) as a function of WF mass flow rate and hot water temperature for a HW flow rate of 8 L/min.

The clearance reduction reduces leakages and the immediate effect is an intake pressure increase, which produces a benefit in terms of power and expander global efficiency -Figure 5(b)- defined as

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the ratio between the measured electric expander power and the one referred to an adiabatic isentropic transformation.Therefore, a minimum clearance gap equal to 10 μm was fixed and the new performances of the whole recovery unit were calculated for a working fluid (WF) mass flow rate and hot water (HW) temperature ranging from 20 g/s up to 80 g/s and from 110 °C (383 K) up to 80 °C (353 K), respectively. A reference value of 8 L/min was chosen for the hot water flow rate. In Figure 6, the power of the recovery unit (a) and efficiency (b) are reported. The efficiency was evaluated as the ratio of the net power produced by the unit and the thermal power provided by the hot water. It can be seen that if the hot water temperature decreases (reservoir whose temperature inside is decreasing), the range of working fluid mass flow rate that produces a useful power decreases, thus limiting the recovery into mechanical energy when the reservoir is discharging. At 110 °C (383 K), the WF mass flow rates range between 14 g/s and 75 g/s, whereas when the temperature decreases to 80 °C (353 K), this range is sensibly reduced (14 g/s - 27 g/s). The maximum power stands at 300 W for a mass flow rate between 30 g/s and 40 g/s and a hot water temperature of 110 °C (383 K). These results agree with the theoretical expectations since the maximum power is expected to be reached when the hot source assumes the maximum temperature. The efficiency of the ORC unit is reported in Figure 6(b), assuming similar isolines distribution when the clearance is reduced. The maximum efficiency stands at 4 %, in good agreement with the literature results of those applications involving the introduction of a recuperative heat exchanger (Ancona *et al.*(2022), Eyerer *et al.* (2020)). Analogies also exist for the expander behavior as an efficiency ranging from 30% up to 60% is observed in Eyerer *et al.* (2020) and Unamba *et al.* (2019)). The results shown in the iso-lines are also interesting in terms of operating range definition and performance of the unit in off-design conditions. As a matter of fact, an "activation line" can be seen observing Figure 6. This line delimits a region of WF mass flow fate and HW temperature, ensuring the plant activation; the "activation line" could be inserted into a model-based strategy of the unit and orient its management according to the temperature inside the reservoir. The data refer to a specific hot water flow rate equal to 8 L/min; a broader analysis for different flow rates gives a working condition map which could be the base of a model-based control. The maps reported in Figure 6 also demonstrate how wide is the region of the off-design performance of the unit. In particular, for a fixed hot water temperature of 110 °C (383 K), in correspondence to a reduction of the WF mass flow rate, the power and efficiency decrease, but the isolines are farther than in the case in which the WF mass flow rate is increased. This means that the power and efficiency reduction presents a lower slope when the WF mass flow rate is decreased from the design point compared to the case according to which WF mass flow rate increases. 502

CONCLUSIONS

In the present paper, the influence of the expander clearance gap reduction on the performance of a micro-cogenerative solar-driven ORC-based power unit was experimentally and theoretically analyzed. The results show that by reducing the clearance gap from 30 μm up to 10 μm, the power and efficiency of the expander grow. The improvement of the volumetric efficiency significantly reduces the leakages and realizes a better filling of the chambers, producing more expansion work. This effect can be achieved not only by reducing the geometrical tolerances but also improving the lubrication of the machine. Thus, to assess the effects of such improvement on the whole behavior of the recovery unit, the operating map of the expander with the lower clearance was obtained and introduced into the whole model of the recovery unit. Results show that the reduction of clearance gaps produces an enhancement of 10.5% and 12% of the ORC unit power and efficiency, respectively. Consequently, the electrical energy produced daily by the unit increases by 11%. Moreover, the map of the expander integrated inside the model of the unit identifies an "activation line", which can be transformed into a model-based-control strategy. Indeed, for a given temperature of the water inside the reservoir which represents the hot source of the unit, the WF mass flow rate range that ensures the activation of the ORC plant is reported as a function of the hot water temperature.

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ACKNOWLEDGEMENT

The authors are grateful to SIVAM S.p.A for the support given in this activity. New subroutines employed in the Scroll model were developed in the framework of the PRIN H2-ICE (Project of Relevant National Interest), funded by the Italian Minister of University and Research.

This book contains the compilation of works contributed to the *7th International Seminar on Organic Rankine Cycle Power Systems* (ORC 2023), held in Seville between the 4th and 6th of September 2023. The event was hosted by Universidad de Sevilla on behalf of the Knowledge Centre on Organic Rankine Cycle Technology (KCORC), incorporated in The Netherlands.

The ORC conference, organized biennially, stems as the only conference that is specific to ORC technology, therefore gathering a diverse community whose affiliation spans across all the interested stakeholders, not only in this particular technology but also and in a broader context, in the energy transition. Original equipment manufacturers, professional associations, end-users, investors, policy makers, academics, scientists feel at home at ORC 2023.

The almost 100 proceedings in this book cover a wide variety of topics, from fundamentals to system integration through component design, accounting for thermodynamic performance as well as component design. In addition to this, and as a new track in 2023, works on heat pump technology were also accepted in order to raise awareness of the strong ties between both technologies, specifically in energy storage applications.

This book provides an excellent overview of the current maturity of power systems based on Organic Rankine Cycle technology for applications as diverse as geothermal and waste heat recovery in industry or downstream of other prime movers (e.g., marine applications). It is also an excellent source of information to understand the current challenges faced by the technology, stemming from a very competitive market and increasingly stringent environmental regulations.

The organizers of ORC 2023 hope that the reader finds this work as exciting as the attendees to the conference and, maybe, make the decision to join the 8th edition to the conference in 2025.

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