

14CNIT-1127

## Energy, exergy and economic analysis of a simple Rankine cycle and an ORC module for power generation using variable flow and temperature industrial exhaust gases as a heat source

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### 1. Introduction

Efficiency is a key factor during the design of a power generation cycle. Especially in the fields where the energy vectors being used are finite or scarce, either in an explicit or implicit way [1]. This can be the case of solar power plants with a molten salt based thermal storage, for example, which are designed with the objective of maximizing the cycle efficiency, because of the nature of solar radiation.

However, nowadays this design philosophy might not be used in industries that benefit from electric generation as a side product, usually by making use of residual heat sources [2], [3]. High efficiency cycles and hence, components, imply higher capital investments that make them harder to opt for. Typically, a more economic and less efficient solution is preferred by industries just looking to leverage any residual energy source. This makes simple Rankine cycles and Organic Rankine Cycle (ORC) modules very appealing technologies to generate electricity, either for self-consumption or as an additional source of income when injecting it to the grid [4].

Both solutions are well spread and considered mature technology, but naturally, that does not necessary imply that they are the most adequate solution in every scenario, depending on several aspects like the characteristics of the available energy vector. While there might not be many thermodynamic constraints when sizing a simple Rankine cycle and choosing its components and connections, ORC modules are usually standard supplier products to which little modifications can be done. Additionally, an auxiliary cycle is needed in the case of the ORC, to perform the heat exchange between the heat source and the power module. This is typically done using a heat transfer fluid (HTF), whose properties allow for efficient heat transmission at the required range of temperatures. For this study, Therminol-66 is the chosen HTF [5], based on the experience and knowledge possessed by Sener Ingeniería y Sistemas, after having developed numerous solar thermal plants using different technologies (central tower and PTC) [6], [7], [8]. Even though ORC modules suppliers provide little to no information regarding the insides of their machines, a complete ORC is modelled using reverse engineering, in order to be able to properly conduct the energy and exergy analyses.

One of the objectives of this research study is to present the current limits of power plant optimization for a representative plant in the range of 1 MWe. This is done considering the boundary conditions given by suppliers who can only offer modular equipment that, not always, are optimal for the available heat source constraints. Furthermore, as a second objective, once the turbine of the steam cycle and the ORC module are selected for a real variable flow and temperature heat source, both cycles are modelled in detail considering all the real constraints found in the exhaust gases system of a specific furnace. This way it is possible to simulate the operation of both cycles for a whole year considering off-design operation conditions, which are critical regarding real-world operation, performance and maintenance.

As a final objective, a detailed exergy analysis is performed on both cycles to highlight the potential improvement of the actual technology level for these type of power plants in the range of 1 MWe. Giving a clear insight on the areas of improvement for a better conversion of available variable flow and temperature industrial exhaust gases into electricity.

Nevertheless, these mentioned alternatives are not the only ones that can be considered in this kind of conceptual studies. Depending on the near future expected efficiencies in the components of supercritical CO<sub>2</sub> cycles, as well as their expected cost reduction, supercritical CO<sub>2</sub> power cycles could become the most compelling alternative for harnessing high-temperature residual heat in these types of industrial applications, based on the sensitivity analysis carried out by Novales et al. [9].

### 2. Materials and methods

This research article arises from a real project being carried out, on an existing copper melting furnace. As it might be expected, numerous constraints (space, layout, auxiliaries) appear since work is to be done on an already existing facility, as opposed to a *greenfield* project. The input data used for the sizing of the components and cycles is as shown in Table 1 and Table 2. These correspond to the daily four operation modes of the copper melting furnace whose exhaust gases are being used, as well as their composition. This is the starting point of the research, where all the subsequent calculations and assumptions are to be made.

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Table 1. Input data regarding the exhaust gases of the industrial furnace. Daily operation cycle.

Operation	Flow <i>kg s<sup>-1</sup></i>	Temperature <i>°C</i>	Duration <i>h</i>
Process 1	4.00	980	13.10
Process 2	2.60	788	5.56
Process 3	2.00	805	3.37
Process 4	5.80	1000	1.97
<b>Total</b>			24.00

Table 2. Constant composition of the exhaust gases from the industrial furnace.

Compound	Molar concentration <i>mol%</i>	Molecular weight <i>kg kmol<sup>-1</sup></i>
O <sub>2</sub>	1.0	32.00
CO <sub>2</sub>	11.0	44.01
H <sub>2</sub> O	20.0	18.02
N <sub>2</sub>	68.0	28.01
<b>Mixture</b>	100.0	27.81

The heat and mass balances to simulate the proposed alternatives, have been computed using Thermoflex, a thermodynamic processes simulation software commercialized by ThermoFlow [10], widely used in the thermodynamic engineering sector. As previously advanced, two different power cycles have been modelled, simple Rankine cycle and an ORC module, under economic and simplicity designing premises, both in the components of the cycles and in their operation. Therefore, the trade-off has been the efficiency of the components and of the power cycles themselves.

The design case corresponds to the period when the furnace is operating at the conditions denoted as *Process 1*, being the cycle and components sized for this case. This choice is not only dictated by the potential for recovering the maximum amount of energy from the exhaust gases (momentarily ignoring *Process 4* due to its infrequency) but also by the extended duration of this operation process throughout the day. Therefore, during great part of the operation cycle, the thermodynamic cycle operates at its design point, minimizing efficiency losses resulting from components operating in off-design modes. The global layout of the proposed solutions for the exhaust gases leveraging is as presented in Fig. 1.

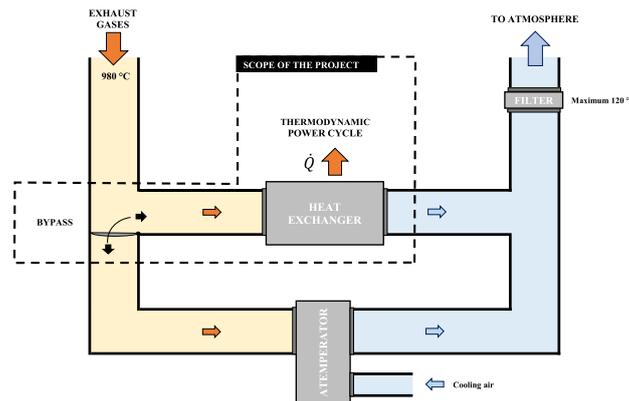


Fig. 1. Simplified diagram showcasing the scope of the project and layout of the proposed solution.

As shown in Fig. 1, a bypass is proposed not only for possible unscheduled outages from the power cycle or heat recovery system, but also for the period during which the furnace is operating at the conditions of the *Process 4*, which imply a higher exhaust gases flow and temperature. Cool air dilution is needed, to ensure that the maximum temperature reached at the final filter before the stack is lower than 120 °C. This cooling component is out of the scope of this research.

### 3. Results

In Table 3 the performance and economic results of the study are showcased. In particular, the calculated annually produced energy, heavily depends on operating conditions and parameters during off-design periods of operation. Because of that, off-design heat and mass balances are computed for the simple Rankine cycle. In the case of the ORC module, a performance curve of the selected ORC model provided by the supplier is used, since the interior of the ORC module is not open sourced.

When comparing both alternatives, it can be observed that the steam cycle option exhibits a higher annual energy production (26.7 % superior) compared to the ORC, translating to higher economic savings when used for self-consumption. However, the total costs of the steam cycle option are also greater (17.9 % higher). As a result, the steam cycle option boasts a shorter payback period than the ORC module (6.89 years versus 7.66 years), indicating a quicker return on the initial investment with the steam cycle option. This is a conclusion that requires careful analysis, as the steam cycle option necessitates of a more specific and frequent maintenance and control tasks, for instance. The requirement to engage qualified personnel to operate the boiler and turbine as well as the potential need to have access to a demineralized water treatment plant, may detract from the attractiveness of this option.

Table 3. Economic comparison between the alternative solutions.

		ST	ORC
Operating hours	<i>h</i>	8 040	8 040
Energy produced	<i>MWh year<sup>-1</sup></i>	5 986.35	4 388.03
Service cost	€	909 987	746 918
Component cost	€	3 017 004	2 667 666
Civil cost	€	926 300	569 002
Other costs	€	303 147	248 824
<b>TOTAL EPC</b>	€	<b>5 156 438</b>	<b>4 232 410</b>
Price of electricity	€ <i>MWh<sup>-1</sup></i>	130	130
Annual savings	€ <i>year<sup>-1</sup></i>	778 226	570 444
O&M expenditure	€ <i>year<sup>-1</sup></i>	30 000	18 000
<b>Payback period</b>	<i>years</i>	<b>6.89</b>	<b>7.66</b>

This underscores one of the strengths of the ORC, which is its minimal maintenance requirements and the lack of need for qualified personnel to operate it.

In summary, both alternatives present their respective advantages and disadvantages, thus the final choice depends on factors such as available budget, investment objectives and resource availability, among others.

Regarding the exergy balances conducted on both alternative cycles, Fig. 2 to Fig. 5 are presented for a better visualization of the exergy distribution and transformations within them. It is observed that in both cases, Fig. 4 and Fig. 5, the primary contributors to exergy destruction in both cycles are shared. These are composed by high-temperature heat exchangers and turbines, components that are responsible for over 90 % of the exergy destruction in their respective cycles. Therefore, if improvements were to be implemented to optimize the exergetic performance of the cycles, special attention would need to be paid to these components.

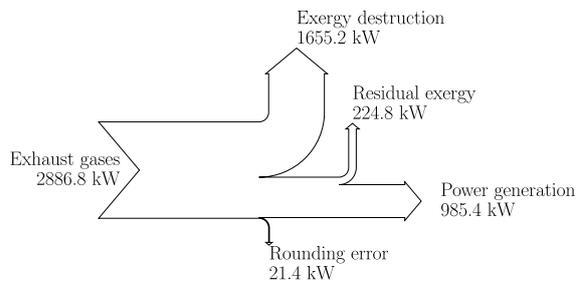


Fig. 2. Sankey diagram depicting the distribution of exergy entering the Rankine cycle.

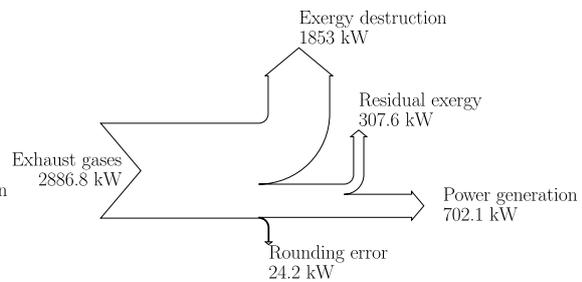


Fig. 3. Sankey diagram depicting the distribution of exergy entering the ORC module and HTF cycle.

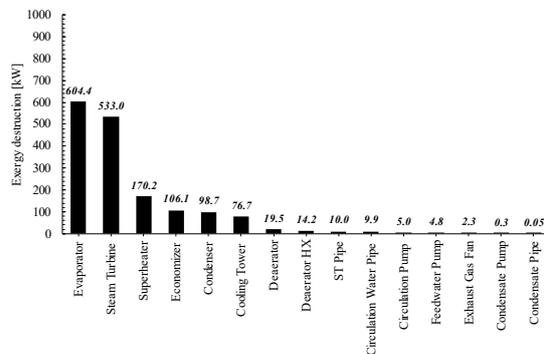


Fig. 4. Exergy destruction by component (simple Rankine cycle).

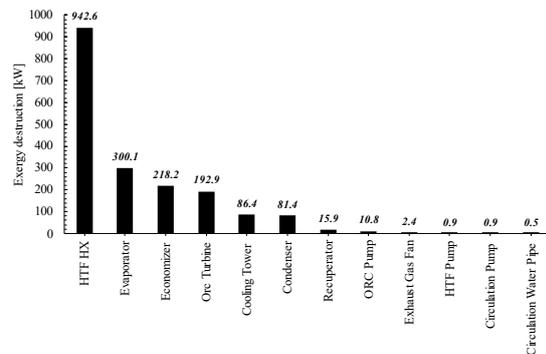


Fig. 5. Exergy destruction by component (ORC module and HTF cycle).

Regarding the steam cycle (Fig. 4), since over 68 % of the total exergy destruction of the system is distributed between the steam turbine and the evaporator, it seems interesting to explore other turbine suppliers with higher efficiencies. However, in these power ranges, the isentropic efficiencies of turbines remain low due to inherent size matters. It could also be interesting to use a HRSG with more than one pressure level, however, this is not relevant in this case as the complexity involved, coupled with the priority given to raw electricity generation over efficiency, means that this alternative is not being taken into account.

In the case of the ORC (Fig. 5), it is observed that by far the greatest exergy destruction occurs in the exhaust gas-HTF heat exchanger. In this case, reducing this value is not easily done, and this destruction can be considered somewhat unavoidable. Additionally, the ORC itself is a black box to the customer since the supplier markets it under standard models with few possible modifications, making it difficult to draw clear conclusions in this matter. Increasing the mean thermodynamic temperature at which the heat is absorbed by the power cycle, would allow for a lower value of the exergy destruction. However, this article showcases how this might be difficult, taking into account the state-of-the-art components and constraints of the discussed mature technologies.

## 4. Conclusions

Purely based on the economic results showcased in Table 3, it may seem that choosing the steam cycle is more appealing. If one is willing to accept the greater complexity that a steam cycle entails, paired with the higher initial capital investment, it could be an interesting choice. It is true that the ORC performs excellently well under partial loads (significantly better than the steam cycle), which is necessary for these cycles which are tightly bound to a certain variable process operation. However, its low base efficiency at its design point results in significantly lower annual generation, meaning that in the medium term, the steam cycle option is amortized earlier despite being more expensive. It is important to remember that the payback periods of the analysed power plants are extremely sensitive to the considered electricity price. The latter plays a big role on the economic aspects of this research, making other scenarios appear if the estimations had been more conservative or optimistic (by the furnace company).

The steam cycle involves additional difficulties both in implementation and operation. Firstly, civil engineering and installation works for installing the components and systems are significantly more complex, specialized, and expensive compared to the ORC. This is because the entire cycle must be assembled on-site, with all the necessary equipment and interconnections.

This is not an issue in the case of the ORC module, as it arrives as a single unit, only requiring connections for input and output flows of oil, water, electricity, and other auxiliaries. It is true that the exhaust gas-HTF heat exchanger and its corresponding HTF cycle still needs to be installed, but in comparison, it usually remains much more affordable and straightforward in the eyes of the customer.

Furthermore, operation and maintenance greatly differ between both alternatives. ORC manufacturers argue that their equipment, once installed and commissioned, require minimal to no maintenance or attention from the operation point of view, eliminating the need for qualified personnel.

The steam cycle is the opposite case, where it may be necessary to hire qualified personnel for operating the heat recovery steam generator, as well as the steam turbine and other equipment. Additionally, the cycle requires regular supervision and intervention by operators, which along with everything mentioned above, might make an ORC module more appealing.

Lastly, from an exergetic perspective, it is interesting to observe how both cycles have room for improvement, as expected. In the case of the steam cycle, if improving its efficiency was of interest, even if it resulted in a slight decrease in electrical power generated, it would be possible to achieve better efficiencies and reduce the total exergetic destruction of the system. For example, this could be achieved by adding multiple pressure levels in the HRSG, which is not feasible in a cycle of this reduced size and characteristics.

In the case of the ORC, it is more difficult to make such improvements due to the fixed nature of the technology, where the supplier keeps most of the knowledge confidential, and makes the modules standard. Proposing specific improvements for this type of cycle would require calculations and studies beyond the scope of the research presented in this article.

Ultimately, this work serves as a preamble to a study in which other technologies will be analysed for residual heat leveraging. Particularly, based on supercritical CO<sub>2</sub>, to be able to compare them to the technologies discussed in this article.

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# 14<sup>th</sup> National and 5<sup>th</sup> International Conference in Engineering Thermodynamics

The Organizing Committee of the 14<sup>th</sup> National and 5<sup>th</sup> International Conference in Engineering Thermodynamics, held in Zaragoza (Spain), from June 4<sup>th</sup> to 6<sup>th</sup>, 2025, hereby declares that the paper entitled

Energy, exergy and economic analysis of a simple Rankine cycle and an ORC module for power generation using variable flow and temperature industrial exhaust gases as a heat source.

has been presented at this edition of the Conference by

**Daniel Pérez**

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Luis M. Romeo

*On behalf of the Organizing Committee*



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# 14<sup>th</sup> National and 5<sup>th</sup> International Conference in Engineering Thermodynamics

We hereby certificated that

## Daniel Pérez

Has attended the 14<sup>th</sup> National and 5<sup>th</sup> International Conference in Engineering Thermodynamics,  
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