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A REVIEW ON SOLAR ORGANIC RANKINE CYCLES TECHNOLOGIES

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Abstract. *The Rankine cycles represents today a strong and competitive power cycle to produce energy from waste heat recovery or renewable sources. This paper brings a review on organic Rankine cycles, a variant of Rankine cycles working with organic fluids, explanting its standard components and how they affect the cycle, common working fluids for the cycle alongside an analysis of the power output from different fluids and a review on a variation of organic Rankine cycles working with solar energy as energy source.*

Keywords: *Organic Rankine cycle, review, solar energy.*

1. INTRODUCTION

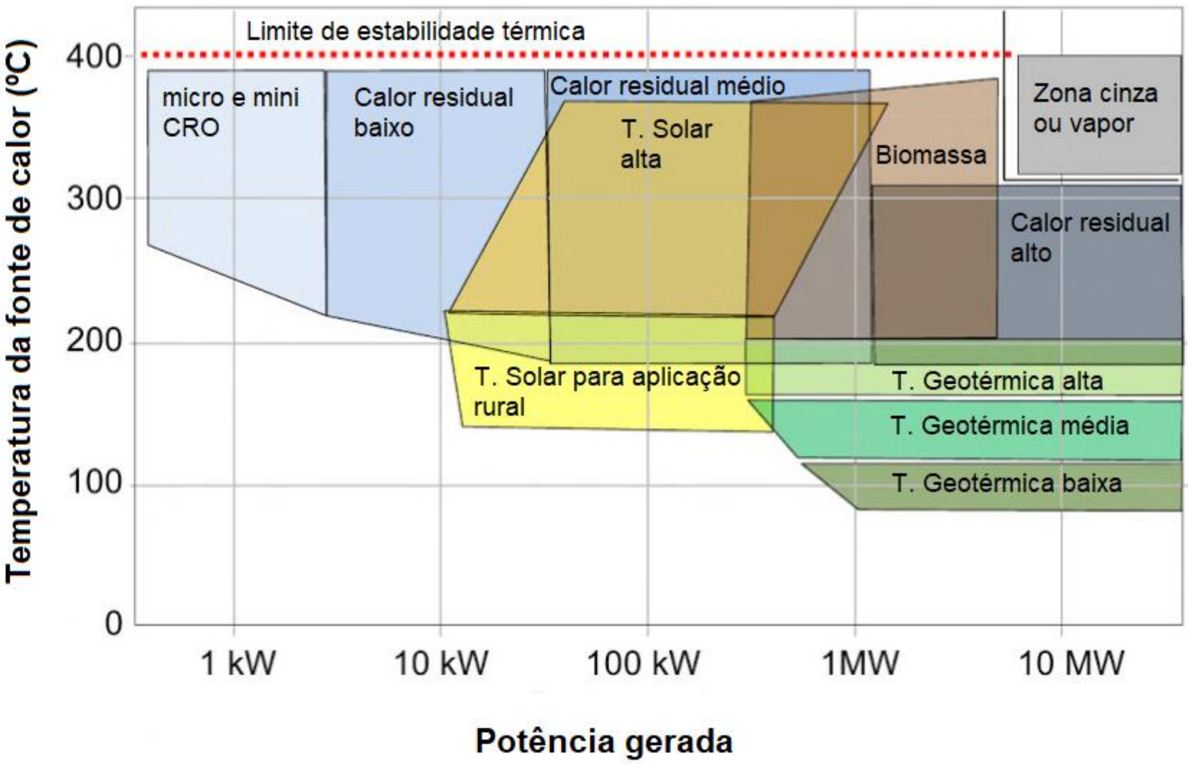
Alternative ways to produce and recover energy are a worldwide concern in the last years, so, renewable energy sources attracted a lot of attention in the past decades due to energy shortage, environmental aspects (Abelowafa, *et al.*, 2018), the Rankine cycle is large utilized to produce useful energy utilizing solar energy, waste heat from industrial process, geothermal energy among others sources of energy to power the cycle.

There are two main types of Rankine cycles, the steam Rankine cycles and the organic Rankine cyles, what differs them is the fluid used in the cycle, while the steam Rankine cycle uses water as working fluid the organic Rankine cycle (ORC) uses organic fluids as working fluids.

This paper intends to make a bibliographic review on solar organic Rankine cycles and it's technologies, since this cycle is an alternative to the common Rankine cycle with organic fluids against the water used on the common Rankine cycle.

Quoilin et al. (2013) and Espinosa (2016) compared the advantages and drawbacks of both techonologies, presenting the diferences between the organic fluids and water, showing that ORCs are more efficient for low and medium temperature heat sources because of its bigger molar mass, higher condensation temperature and lower evaporation temperature compared to water those have a major impact on the complexity of the equipements, thus making this, a cheapest cycle. Quolin (2013) also make a analysis of the T-s curve of the organic fluids, and based on that comparison is seen that due to properties such as lower vaporization temperature, why the ORCs work better with low and medium heat sources.

Figure (1) is a diagram made by Macchi e Astolfi (2016) with the heat source temperature by the power generated by the ORC, and as it can be seen for low and medium temperature heat source, ORCs are applied on four types of heat sources, waste heat recovery from process and equipements, biomass, geothermal and solar energy (Macchi e Astolfi, 2016), thus showing a wide variety of applications and why the ORCs represent an interesting cycle to be studied.



Fonte: Adaptado de Macchi e Astolfi (2016).

2. SOLAR ORGANIC RANKINE CYCLE

Organic Rankine cycles works with basically hydrocarbons, siloxanes and refrigerants as working fluids, a great advantage of these fluids is the possibility of working with lower temperatures. As it can be seen on Figure (2) the organic fluids utilized by the cycle contemplates more than one class of fluids, but, according to (Landelle, *et al.*, 2017) 52% of the working fluids are HFC, 20% are HCFC, 7% are hydrocarbons, 6% HFE, 4% mixtures, 2,5% PFC, 2,5% CFC, 2,5% HFO and 5% of other fluids, and this data provides us with information that the biggest part of organic Rankine cycles work with refrigerants as working fluid, according to (Landelle, *et al.*, 2017) the biggest portion of utilized working fluids are composed basically by R245fa (52%), R123(18%) and R134a(7%), on solar organic Rankine cycles more specifically the R245fa and R134a are largely used for applications that work below 250 ºC according to (Abelowafa, *et al.*, 2018).

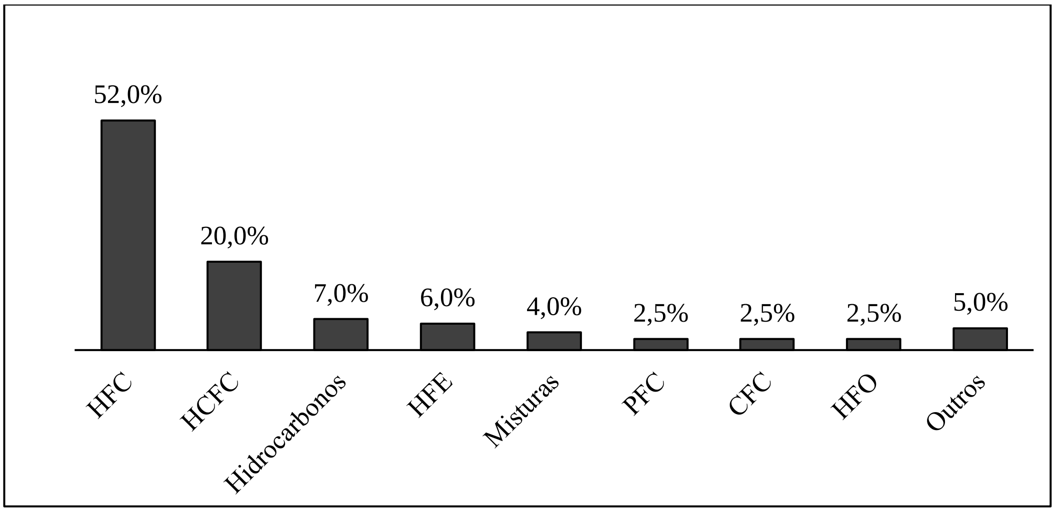


Figura 1. Percentual de utilização de fluidos orgânicos em CROs, adaptado de Landelle *et al.* (2017).

The organic Rankine cycle can also be constructed on its regenerative configuration, on this configuration a regenerator is placed between the pump and the evaporator to pre-heat the fluid with the exit of the turbine and at the same time it cools down the fluid entering the condensator, this process increases the efficiency of the cycle therefore reducing the irreversibility on the system (Javanshir, *et al.*, 2017), regenerative Rankine cycles were found to have a greater efficiency while working with dry fluids as it is presented by (Hung, 2001).

Among the solar Rankine cycles there are two configurations called HTF (Heat Transfer Fluid) and DVG (Direct Vapor Generation), (Abelowafa, *et al.*, 2018), with HTF technology most used due the ductility of the system with more mobile parts, even despite the greater irreversibility along the process. A comparison between HTF and DVG methods are shown in Table 1.

Table 1. Comparison between HTF and DVG methods. Adapted from (Abelowafa, *et al.*, 2018).

	HTF	**DVG**
Technology Stage	Commercial	Demonstrative
Process Stability	Stable	Less stable
Configuration	Simple	Complex
Control Effort	Lower	Higher
Scaling-up	Easier	With additional costs
Performance Enhancement	Limited	Promising
Operating Temperatures	Limited	Promising
Efficiency	Medium, limited	Higher, promising
Thermal Storage	Less expensive, commercial	Expensive, demonstrative stage
Fluid Toxicity	Yes	No
Environmental Risks	High	Low

According to (Muñoz, 2013) the solar irradiance on earth's surface is approximately 750 w/m². For the use of this energy there are two ways: Solar photovoltaic and Solar Thermal.

Solar thermal energy uses collectors to concentrate the irradiation of the sun in a solar collector, which can be concentrating or non-concentrating collectors. Table 2 lists the different solar collector technologies commonly used and their typical temperature range.

Table 2. Solar thermal collector technologies and the corresponding temperatures. Adapted from (Abelowafa, *et al.*, 2018).

Technology	**Temperature (ºC)**
Flat Plate Collector (FPC)	30-100
Advanced Flat Plate Collector	80-150
Compound Parabolic Collector (CPC)	70-240
Evacuated Tube Collector (ETC)	90-200
Parabolic Trugh Collector (PTC)	70-400
Linear Fresnel Reflector (LFR)	100-400
Dish Concentrators	500-1200
Heliostat Field + Central Receiver	500-800

When higher is the temperature of the collector, lower is the efficiency of the solar cycle. That occurs because the heat losses with the environment grow. But higher temperatures, increase de performance of the thermal machine. The total yield stays between 7% up to 9% (Muñoz, 2013).

Aboelwafa et al. (2018, Li et al. (2013), Delgado-Torres and García-Rodríguez (2012) and Peñate (2012), studied alternatives applications of the ORCs, such as water dessalination by reversal osmosis,
and they showed that the ORC is the lowest energy consumption method for water dessalination by cubic meter of water, although, dessalination is the expensivest way to get water.

2.1. Components

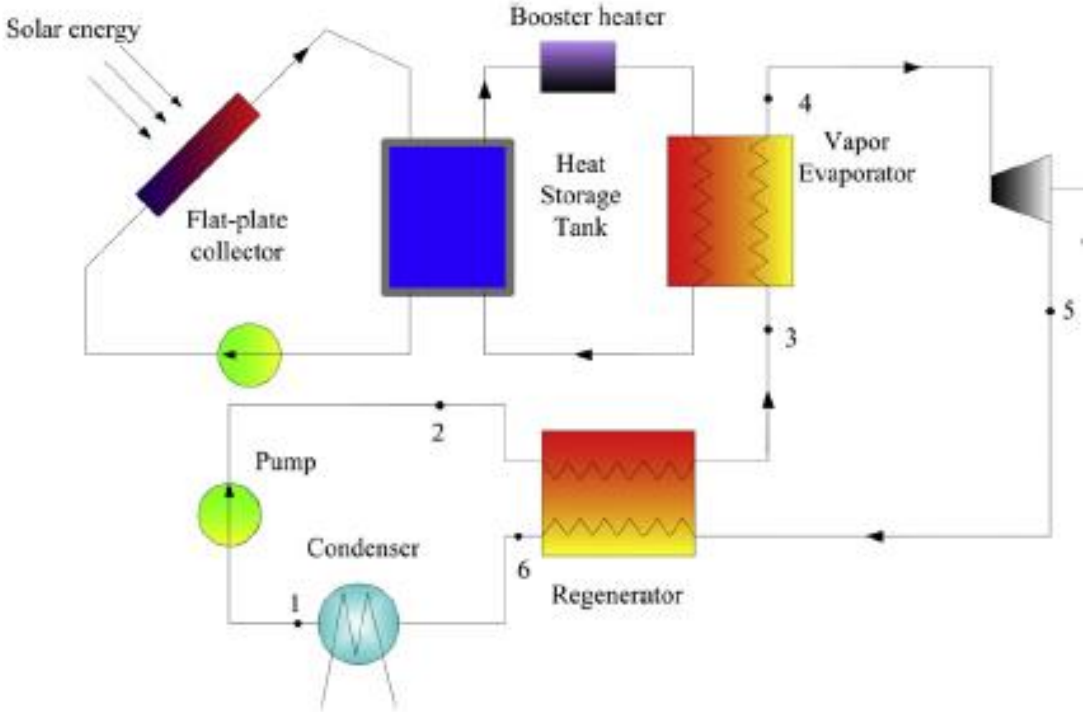
Rankine cycles are composed by four standard equipements, they are the expander, the condenser, the pump and the evaporator, as it is stated by (Landelle, *et al.*, 2017). The expander is a fundamental component to study when analyzing the power capacity of the cycle since the expander efficiency is correlated with its power scale, also according to (Li Zhao, 2013) along with the power scale of the expander, parameters such as pressure ratio, lubrication requirements, complexity, reliability, cost, among others have impact on the expander choice for the system.

Pumps are used to generate a mass flow of the working fluid on the cycle, however the most important parameter of the pump is its power consumption because it interferes directly on the power output of the system since some portion of the power produced by the expander is used to drive the pump, (Quoilin, *et al.*, 2013) references the relation between the work generated by the expander and the work used by the pump as the BWR (Back Work Ratio) and demonstrates that for steam Rankine cycle the BWR is usually low, but for organic Rankine cycle the BWR is a considerable parameter for the system stating that the pump efficiency is important for low temperature cycles, such as organic Rankine cycles working with some refrigerants as described before on this paper.

Evaporators and condensers doesn’t represent a major importance on studies on organic Rankine cycles, because the main point in using organic Rankine cycles is to change specially the evaporators to find new applications for renewable energy sources within this cycle, so, despite they classify the cycle, the major interest of study is the power scale generated by the expander, although these components doesn’t seem to important about their parameters for choice on the system, (Helvaci and Khan, 2017) showed that, on the mathematical model of the cycle, both components need attention since the fluid flowing through them shows significant changes, such as single-phase flow to two-phase flow on the evaporator, meaning significant changes on the result of a mathematical model of the cycle.

Wang et al.(2018) studied the influence of a thermal storage on the ORCs, it can be seen on this study that a thermal storage brings benefits to the cycle such as the capacity of working in times that there is no sunlight, thus, increasing the cycle daily efficiency.

Figure (3) is a diagram made by Wang (2013) of a regenerative solar ORC built on a HTF configuration with a thermal storage.



Fonte: Wang (2013)

2.2. Solar Energy

As it were raised by (Moreira, 2017) the solar radiation on earth surface is about 750 W/m² and it is a important energy source, since it can be used in the whole planet surface, that means regions with difficult access or costly energy, and allied with an ORC, the (Moreira, 2017) also stated that linear and parabolic solar concentrators work better with ORC’s, and usually are utilized for low electrical power generation, between 1 to 10 kWe specially on remote places.

Based on a linear concentrated solar collector field, Cioccolanti et al. (2018) made a simulation of a ORC conected on a linear Fresnel reflectors solar field, with a thermal energy storage tank, as a result of this simulation, they found out that, even with a unoperactive ORC cycle for about 4384 hours in a year (more than half of annual hours) the ORC could still produce about 5100 kWhe, wich is a considerable amount of energy for households, demonstrating that solar energy with an ORC is a good alternative to produce clean and sustainable energy.

For solar energy driven organic Rankine cycles, (Li, 2018) argues about the necessity of a thermal energy storage, due to climate changes, and also he presents the need of using the thermal energy storage to stabilize the system, since, according to him, the power output of the cycle suffer a great impact when occurs a variation of a heat source.

ORCs have a great installed capacity of energy generation around the world, about 3,3 GWe, however, the solar ORC represents a range smaller than 0,1% of the full capacity, as it was stated by Hromadka and Martinek (2017).

3. FLUID COMPARRISON

Among the working fluids used for organic Rankine cycles, there are some different classes that divide them, such as wet fluids, dry fluids and isentropic fluids, among others, this classification considers the fluids properties involving parameters such as critical temperature, critical pressure, maximum output power, and represents a big matter on the evaluation of the cycle, besides, Tchanche et al. (2011) also added that is possible to work with dry and isentropic fluids on saturated vapor since there is no risk of erosion on the turbine spades.

Bao (2013) presented the fluid propertis wich influence its selection as working fluid, along with a descripton for why those properties are so important. Briefly, the importante properties on the selection of a working fluid for a ORC are, the vaporization latent heat as higher it is allows most of the avaliable heat do be added during the phase change operation, fluid density have a major importance because a low density leads to a high volume flow rate, thus increasing the pressure drop in the heat exchangers, specific heat should be low to decrease the work consumed by the pump, critical temperature wich implies on the system efficiency, boiling temperature, as higher it is, increases the thermal efficiency, the freezing temperature must not be higher than the lower temperature of the cycle, molecular weight and molecular complexity as they impact on the expander complexity, low viscosity is desirable to maintain low friction and good conductivity to achieve a high heat trasfer.

Figure 1 presents a conventional Rankine cycle with its 4 basic components and a T-S diagram with the ideal state of the fluid in each steady state process. Process 1>2 consists of an isentropic expansion of the fluid in the turbine, process 2>3 represents a isobaric rejection of heat in the condenser until the fluid becomes saturated liquid state, process 3>4 consists of a isentropic increasing pressure using the pump, 4>1 shows a isobaric heat transfer in the evaporator until the fluid is in saturated vapor state.

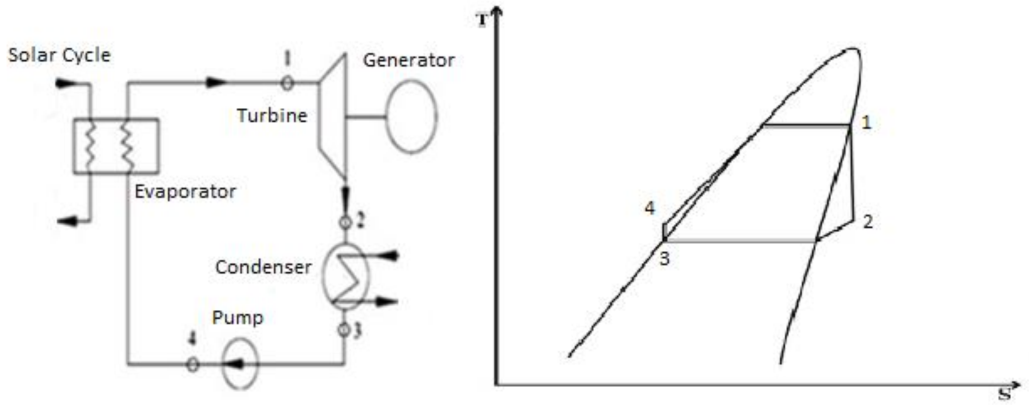


Figure 1. Simple cycle ORC, configuration and e diagram T-S. Adapted from (Muñoz, 2013).

Figure 2 shows an analysis of the power produced by the organic Rankine cycle and the thermal efficiency of the same by changing the temperature of the fluid at the turbine inlet using different working fluids.

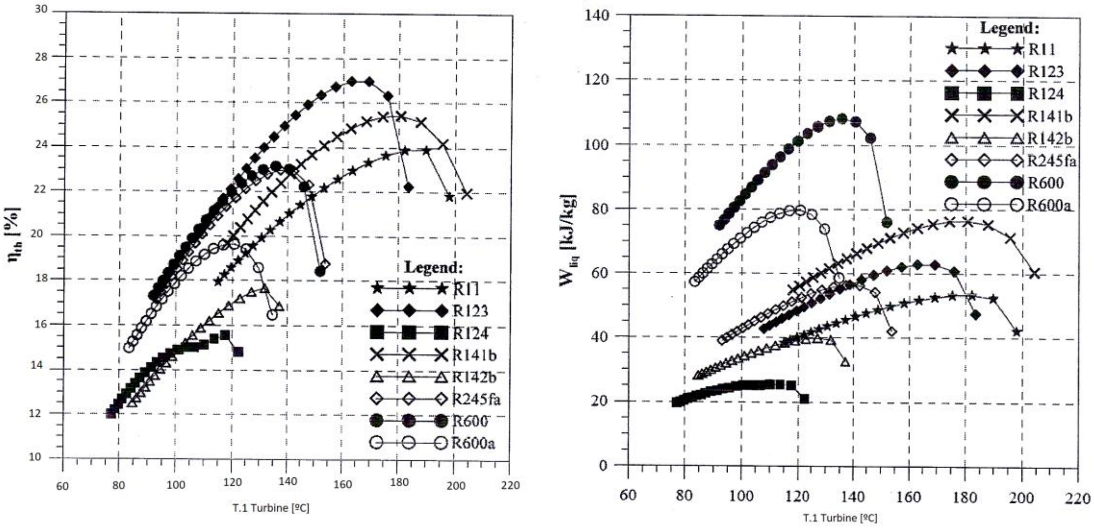


Figure 2. Generated power and efficiency for an ideal cycle with temperature variation at the turbine inlet using different working fluids. Adapted from (Moreira, 2017).

From the results of figure 2, it is possible to note that as well as the efficiency, the power generated in the cycle increase with the increase of the temperature at the turbine inlet, but the cycle loses this characteristic when the temperature approaches to the critical temperature of the fluid.

From that comparison the (Moreira, 2017) also claims that the most used working fluid in the organic Rankine cycle is the R600 although it doesn’t have the greater efficiency among the common used working fluids, this fluid have the higher power capacity output for the cycle.

Uusitalo et al. (2018) conduced a study on the different fluid types and its critical properties, and concluded that the critical temperature of the fluid must be close to the heat source of the cycle for the ORC to achieve a higher efficiency, according to his study.

4. CONCLUSION

The results showed the importance of analyzing the technologies involved in the solar organic Rankine cycle according to the desired application, once that changing a component, for example the type of solar collector, the temperature at the entrance of the turbine varies and, consequently all the results of power and efficiency of the ORC cycle will change, it's because these quantities are related.

It is also possible to notice that there is an optimum temperature range for each working fluid where the maximum efficiency and maximum power of the ORC can be extracted.

As it can be seen too, there are some relevant aspects to analyze when studying solar Organic Rankine cycles:

a) The working fluid selected should have a critical temperature close to the heat source temperature, because this affects the cycle efficiency.
b) Dry and isentropic fluids are preferred for ORCs, since they usually enters the turbine as superheated vapor and saturated vapor respectively, thus, possibilting a cheapest installation for the system and simpler equipements, especially the turbine.
c) The most important equipements to analyze when studying the ORC is the expander, since there are many types avaliable working in various ranges of power output scale, although, turbine expanders appears as the most commonly used in the literature, since their power output range is large.
d) Solar energy is a good heat source for ORC, but, despite the heat source capacity it is little used to generate energy.

5. ACKNOWLEDGEMENTS

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