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A PROPOSE FOR AN ORGANIC RANKINE CYCLE COGENERATION SYSTEM

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Abstract. *This work aims to study a system that involves the cogeneration of an organic Rankine cycle (ORC). Some refrigeration fluids were analyzed to be worked with, being chosen the refrigerant R245fa. A cogeneration cycle was proposed, involving a Rankine cycle coupled with the ORC, aided by computational tools, such as EES (engineering equation solver) to proceed thermodynamic properties of the refrigerants and a spreadsheet. This arrangement can improve its thermal efficiency. A great advantage of this proposal is a better improvement of power surplus in the industrial system, mainly if there is a low thermal efficiency.*

Keywords: *Thermal systems; cogeneration; Organic Rankine cycle.*

1. INTRODUCTION

An analysis of the socioeconomic environment that human being lives, it is possible to note the need for new energy resources, mainly cleaner and more efficient. This is important to reduce the energy use and consumption of fossil fuels that affect our environment.

New energy generation sources are constantly in studies, as well as the improvements of the existent ones. Therefore, a more efficient way of this process is tried to be reached, such as using their surplus energy to increase their efficiency by using a cogeneration system, as this study demonstrates.

Organic Rankine Cycle (ORC) is a thermodynamic system where water is replaced by an organic fluid that has a lower specific work and higher density, that becomes easy to project a system with a low capacity steam turbine, from some kilowatts until 1 or 2 MWe (Mazurenko et al, 2013).

An ORC system can be used, with few modifications, together with many heat sources. This is due to the technological maturity of its components, used in the refrigeration industry. Besides, it makes possible the power generation (Carlão, 2010).

Thus, the purpose of this work is understanding a coupling of an organic Rankine cycle with a conventional Rankine cycle and the impact in the power production. It may be a good alternative to small plants.

There are many fluids available for use in the ORC system that must be considered in the designing phase. It becomes an advantage, making the ORC system suitable for a wide range of heat sources.

It showed a list with 47 fluids to be used in ORC systems (Astolfi, M. et al, 2017b), with their critical pressure and temperature as well the operating maximum temperatures that leads to the thermal stability. This stability indicates the limit that fluids are decomposed into lighter compounds, changing their thermodynamic properties.

Further analysis is required in the choice of fluid, since organic fluids can be selected by various criteria and compositions, such as hydrocarbons, refrigerants and siloxanes. However, only a small number of fluids are commonly used in commercial systems because ORC manufacturers tend to limit the working fluid to a few previously used in plants, the most common being R134a, R245fa and siloxanes (Astolfi, M. et al, 2017a).

ORC system use is increasing around the world. Research and some practical use have been in progress; some examples of these applications are:

a- Studies in cogeneration or trigeneration system, aiming power production and fresh water/cooling and the possibility of power production, fresh water, and cooling. Power is supplied by the Rankine cycle, fresh water by a desalination system and the cooling by an absorption system (Mohammadi and McGowan, 2018).
b- Integration with renewable sources, for example using concentrated solar power with the ORC system (Borunda *et al.*, 2016), becomes a good option for industrial processes at medium temperature.
c- An integrated system with gas turbine and ORC system, optimised by thermodynamic and thermoeconomic conditions (Khaljani et al., 2015).
d- In a triple power cycle (Srinivas and Reddy, 2014), including a Rankine Cycle, Brayton Cycle and Organic Rankine Cycle, the authors integrate these cycles aiming increasing the power generation performance.

2. CASE STUDY

2.1 Cogeneration ORC System

In industrial plants, there is a high potential for residual heat recovery, allowing the implementation of ORC systems having the residual heat recovered as the energy source. However, both hot source temperature and required power output should be analyzed for this implementation. Although it has a high potential of use at a low cost, the recovery technology of rejected heat through the Rankine Organic Cycle represents only 9-10% of the CRO facilities in the world (Enertime, 2011 apud Mascarenhas, 2014).

This cogeneration system aims to analyze the thermal efficiency of a conventional Rankine Cycle with extraction turbine so that steam extraction from the Turbine 1 can be used as the heat source of the ORC evaporator from the open feedwater heater (OFH).

Rankine cycle has the following components: a boiler, an extraction steam turbine, a condenser, pumps, and an open feedwater heater to fit the steam quality to the organic fluid passing through the heat exchanger.

The organic Rankine cycle is interconnected to the Rankine cycle by the heat exchanger. Their components are a turbine, a condenser and a throttle valve.

Thermodynamic analyses were supported by the EES (Engineering Equation Solver) software, due to the R245fa thermodynamic properties database. Thermodynamic properties of water is obtained by the thermotables add-on for Excel (Woodbury *et al.*, 2017) so the input of thermodynamic data is simplified. Moreover, the solver command can be useful to determine the best results for the simulation.

Another implementation is possible by using an Excel command if thermodynamic properties of R245fa is available. This command consists in finding the properties (i.e. enthalpy, entropy, or other) knowing the independent variable. This resource is successfully used with the air properties as ideal gas table in other authors' studies.

The result of this limitation is the properties of the ORC refrigerant are fixed and cannot be changed by the solver, making the analysis more restricted in its operating range.

The ORC is the same as a Conventional Rankine Cycle in its design, distinguishing itself by the working fluid used, in addition to the different equipment. The temperature at the inlet of the turbine in the steam cycle should be above 450 °C to avoid condensation of the water when undergoing expansion in the turbine (Quoilin, 2011).

The need for superheating is eliminated in the ORC, since the fluid remains superheated at the expansor outlet, unlike the Rankine cycle. With no condensation forming, the chances of erosion in the turbines are reduced, increasing their life cycle (Quoilin, 2011).

One situation to consider is the boiler pressure. While in the steam cycle the pressure can reach 70 bar, in the ORC its value can reach approximately 30 bar (Quoilin, 2011). Working at a very high pressure has a negative impact in terms of operating risks and the need of a more resistant structure and equipment due to high thermal stress; also, increasing costs on investment, installation and maintenance.

It is noticed that thermodynamic states showed in Fig. 1 are described in Tab. 1. In state 2 there is a steam flow rate extraction (y) that will be summed with the condensation flow rate (1 – y) in the open feedwater heater, in the state 6.

Table 1 – Thermodynamic states of the cogeneration system.

STATE	DESCRIPTION	CYCLE
1	Output boiler	**CR**
2	Turbine extraction	
3	Turbine outlet	
4	Condenser outlet	
5	Pump 1 outlet	
6	Open feedwater heater outlet	
7	Evaporator outlet / Pump 2 inlet	
8	Pump 2 outlet	
A	Evaporator outlet	**ORC**
B	Turbine outlet	
C	Condenser outlet	
D	Evaporator inlet	

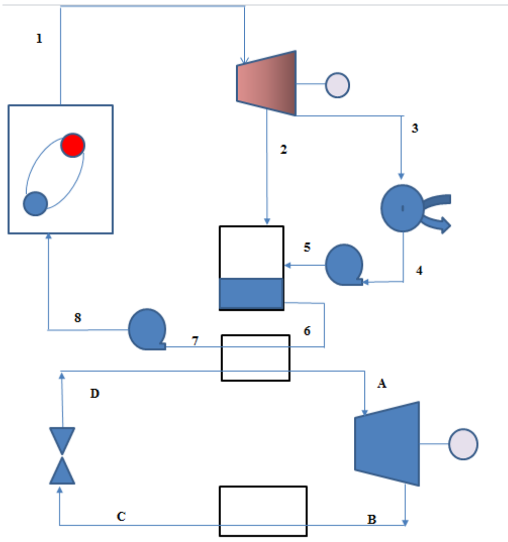

Figure 1 - Scheme of the RC-ORC system.

Another problem in working with this integration is determining the operation temperatures of the ORC and the OFH, so that the extracted steam properties do not exceed the refrigerant properties, causing either infeasibility or the need to search another refrigerant on this study.

Considering other technologies and cycles analyzed, ORC has a considerable relevance as it allows the thermal use of heat waste recovery or from a source of low temperature. Thus, its effective use in a combined cycle is analyzed, making a better thermal utilization of it.

2.2 WORKING FLUIDS

The main feature of ORC for other thermodynamic cycles is the use of an organic compound as the working fluid. In the application of an ORC, organic substances with refrigerant characteristics are used, such as fluorocarbons and hydrocarbons (Herreria, 2012).

The performance determining factor of an ORC is the chosen working fluid. In this selection, it is necessary to carry out an in-depth analysis of the cycle that needs to be developed, as such choice is fundamental to its success. The working fluid is analyzed to maximize the thermal efficiency and net power of the cycle.

When opting for an organic fluid, it is good practice to consider environmental impact factors, as most of them have elements in their compositions that are toxic or inappropriate for the environment. The fluid must not be corrosive, toxic, flammable, or present high levels of auto-ignition. These characteristics are fundamental to guarantee the safety, not only for the system operators, but also of for population close to the plant (Enertime, 2011 apud Mascarenhas, 2014).

Evaluations on economic aspects make the selection process much more rigorous and detailed. The analysis of each specific case is necessary to the best choice of the fluid. In the present study, it was considered the thermodynamic analysis of fluids according to the literature. Economic and environmental aspects were not considered.

The R245fa refrigerant was selected for this analysis because it is usually a working fluid for the Organic Rankine cycle with low potential for aggression to the ozone layer and its high critical temperature value, as shown in table 2.

Table 2 – Properties of the R245fa (1,1,1,3,3-Pentafluoropropane)

Molecular weight (g/mol)	134,05
Critical pressure (MPa)	3,64
Critical temperature (ºC)	154,1

(Martins, 2015)

2.3 MATHEMATICAL EQUATIONS

Thermodynamic analysis for this cogeneration system was realized considering the enthalpy and entropy database of the EES software for the refrigerant fluids properties. The RC enthalpy was obtained from the mass and energy balance, as follows.

Equations (1) and (2) present the enthalpy in the turbine extraction and in its outlet, respectively, Eq. (3) and (4) in the pump 1, Eq. (5) in the open feedwater heater, Eq. (6), (7) and (8) in the evaporator and pump 2.

$$h_2 = h_1 - \eta_{t,1st}\left(h_1 - h_{2s}\right) \tag{1}$$

$$h_3 = h_2 - \eta_{t,2st}\left(h_2 - h_{3s}\right) \tag{2}$$

$$h_{5s} = h_4 - \upsilon_4\left(P_{5s} - P_4\right) \tag{3}$$

$$h_5 = h_4 + \left(\frac{h_{5s} - h_4}{\eta_{5s}}\right) \tag{4}$$

$$h_6 = h_D + \eta_A\left(h_A - h_D\right) \tag{5}$$

$$h_7 = h_6 + \frac{m_{ref}\left(h_A - h_D\right)}{m_{st}} \tag{6}$$

$$h_{8s} = h_7 - \upsilon_7\left(P_{8s} - P_7\right) \tag{7}$$

$$h_8 = h_7 + \frac{\left(h_{8s} - h_7\right)}{\eta_{p2}} \tag{8}$$

2.4 PRELIMINARY RESULTS

EES software has thermodynamic properties of the R245fa in its library, allowing to determine the enthalpy and entropy values of the thermodynamic cycle. The obtained results of the cogeneration cycle are presented in Tab. 2.

The studied case was considered as a real Rankine cycle. In this case, the extraction mass flow rate was about 8,8%.

R245fa is a working fluid non-flammable and non-toxic. Its Ozone Depletion Potential (ODP) is zero, with no danger for the ozone layer. It must be a substitute for the R123 and R11 in high-temperature heat pumps and in heat recovery cycles, as the ORC (Carlão, 2010).

Table 2 - R245fa Thermodynamic analyses results

	States	P (kPa)	T (ºC)	h (kJ/kg)	s (kJ/(kg.K))
CR	1	2000	400.000	3248.227	7.129
	2s	1500	357.337	3163.970	7.129
	2	1500	361.219	3172.396	7.129
	3s	10	45.801	2583.887	8.149
	3	10	76.539	2642.738	8.149
	4	10	45.820	191.812	0.649
	5s	1500	45.867	193.318	0.649
	5	1500	45.886	193.397	0.650
	6	1500	108.404	455.590	1.400
	7	1500	131.049	551.630	1.645
	8s	2000	131.095	552.165	1.645
	8	2000	131.101	552.193	1.645
ORC	A	1574.0	110.000	479.6	1.795
	B	179.2	53.700	449.4	1.826
	C	177.2	30.000	239.1	1.135
	D	1574.0	30.000	239.5	1.133

Notice that the RC with the OFH (also named deaerator) is commonly used in sugarcane plants as seen in some studies (Alves *et al.*, 2015, Joppert *et al.*, 2017, Burin *et al.*, 2016). Although this study makes a simple analysis in plant configuration terms, it is a good practice to make a better use of the residual heat, supply refrigeration to the industry, and to increment the power production due to the use of the expansor.

Initially, is was considered to apply some data of the sugarcane industry but, as mentioned above, it is important to choose the range temperature of the refrigerant used. Otherwise, the refrigerant will suffer chemical decomposition (Quoilin and Lemort, 2009).

Astolfi et al. (2017b) present a comparative data of different refrigerants including their critical and maximum operating temperature as well the critical pressure. It is possible to compare Table 2 results with the authors paper showing that R245fa has not reached its limit, neither in temperature (110 ºC instead of 150 ºC) nor pressure (1,5 MPa instead of about 2,8 MPa).

An important feature regarding the thermodynamic characteristics of organic fluids is the possibility of having a saturated vapor curve in the temperature-entropy diagram with positive slope (dry fluid) or infinite (isentropic fluid). This fact results in superheating the expansor exhaust, avoiding the problem of the turbine outlet condensation (Martins, 2015).

3. COGENERATION CYCLE RESULTS

The cogeneration process efficiency (Eq. 9) is calculated with the ratio of the net work to the added heat of the system.

$$\eta_1 = \frac{W_{net}/\dot{m}}{Q_{in}/\dot{m}} \tag{9}$$

And the work done is the relation between the different works in the system. So, there is power being generated in Rankine and ORC turbines and in the pumps 1 and 2, consuming power. Equation 10 shows this relation:

$$\frac{W_{net}}{\dot{m}} = \frac{W_{st}}{\dot{m}} - \frac{W_{p1}}{\dot{m}} - \frac{W_{p2}}{\dot{m}} + \frac{W_{\exp}}{\dot{m}} \tag{10}$$

Table 3 presents the heat and power consumed and produced in the system, as well as the efficiency of the studied case.

When comparing power output in the turbine and expansor, the latter produces only 5% of the total power. It may seem small enough but becomes more attractive than consuming power in compressors. This fact can be a great advantage for this technology.

Table 3 – Results to the analyzed case.

COGENERATION CYCLE RESULTS	
Q_{in}/m (kJ/kg)	2696.034
W_{st}/m (kJ/kg)	558.872
W_{p1}/m (kJ/kg)	1.445
W_{p2}/m (kJ/kg)	0.563
W_{exp}/m (kJ/kg)	30.200
W_{net}/m (kJ/kg)	587.064
η (%)	21.775

It must be noticed that the ORC shows an efficiency about 13 to 15%. When residual heat recovery occurs using an absorption chiller, it is possible to reach a 23% efficiency (Invernizzi et. al, 2011).

In the same way, RC can present a low efficiency, mainly in sugarcane plants, but its thermal efficiency range is between 15 to 30% (Nascimento, 2015).

4. CONCLUSION

The main objective of this work was reached through the cogeneration system thermodynamics. With this, it is noticed that the ORC efficiency increases when coupled with the conventional Rankine cycle in the cogeneration system.

It is shown that the boiler inlet heat does not present a great change when using low-pressure R245fa.

It was not performed an economic analysis to determine what fluid will be used primarily.

In this work, it is concluded that a solution involving the combined cycle studied, it is necessary to use comparative simulations in which different equipment, working fluids, and fuels can be tested. This evaluates the system performance and the efficiency in meeting installation demands, as well as choosing the feasible solution for the use of the residual heat recovery.

Some future analysis can be considered, such as:

a- Analyze other refrigerants in other range of conditions to understand the cycle behavior;
b- Implementation of thermodynamic table in Excel to integrate the spreadsheet, avoiding manual data entry;
c- In an optimization analysis, adjusting restriction variables to make solver work better;
d- Study other RC temperature and pressure range, allowing its components to be increased in its capacity;
e- Incorporate studies of fuels to be burned in the boiler and their impact in the cycle. A prediction of the low heat value can be an interesting result to determine the use of renewable resources.

ORC systems have a great potential to replace conventional refrigeration cycles, as the power output makes it attractive. In addition, the use of refrigerants with low ozone depletion potential makes it environmentally interesting.

Finally, Rankine-ORC cycle can be an interesting alternative to the energetic exploitation of industrial plants which have their energy production being underutilized.

5. ACKNOWLEDGEMENTS

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