18th Brazilian Congress of Thermal Sciences and Engineering
November 16-20, 2020 (Online)

# ENC-2020-0445
# ORGANIC RANKINE CYCLES OPTIMIZATION FOR ELECTRICITY COGENERATION IN A CEMENT INDUSTRY

**Luiz Fernando Moreira**
Pontifical Catholic University of Minas Gerais, Department of Mechanical Engineering 500 dom José Gaspar Avenue, Belo Horizonte, MG, 30.535-901, BRAZIL
luizfmoreira@hotmail.com

**Felipe Raul Ponce Arrieta**
Pontifical Catholic University of Minas Gerais, Department of Mechanical Engineering, 500 dom José Gaspar Avenue, Belo Horizonte, MG, 30.535-901, BRAZIL
IBMEC - Belo Horizonte, 300 Rio Grande do Norte Street, Funcionários, Belo Horizonte, MG, 30.130-130, BRAZIL
Felipe.ponce@pucminas.br

***Abstract*** *To show the results of optimization of the electricity cogeneration with organic Rankine cycles (ORCs) in cement industry with 3.500 ton of clink daily capacity in the Brazilian energy scenario is the main purpose of this work. The thermodynamic and economic optimization's results for four ORC configurations are presented for three organic fluid. The results were obtained using the mass, energy, entropy, exergy, and cost modelling coupled with genetic algorithm. The modelling was solve using Engineering Equation Solver (EES) software. From the thermodynamic point of view is possible to state that the R141b fluid proved to be more attractive for applications in ORC without superheating with net power generation ranging from 4,565 kW to 5,541 kW, with exergetic efficiency between 41.75% and 49.70%. In ORC with superheating, the R11 fluid was more attractive with net power generation ranging from 5,043 kW to 5,614 kW, and exergetic efficiency between 46.15% and 50.59%. From the economic point of view, the R123 fluid was more attractive with the lowest values of specific investment cost (3,516 R$/kW) and electricity generation (0.1065 R$/kWh) simple subcritical ORC with superheating. From the aforementioned results it can be affirmed that, among the studied fluids, R141b becomes the most attractive for cogeneration in the cement industry because it presents the best thermodynamic performance without losing much economic competitiveness when compared to the economic results shown by R123 and R11.*

***Keywords:*** *Organic Rankine cycle, Cogeneration system, Cement industry, Genetic algorithm*

## 1. INTRODUCTION

The end of the 19th century marked the beginning of cement production in Brazil. The first cement plant in the country was installed in 1897 in the state of São Paulo and from then on, other companies entered this segment. Currently Brazil is among the 10 largest cement producing countries in the world.

According to the Energy Research Company (EPE), the cement sector in Brazil is the eighth largest consumer of electricity in the entire industrial segment of the country (EPE, 2016). Wang, Dai e Gao (2009) and Varma e Srinivas (2015) they point out that there are opportunities to generate electricity in cement plants at an attractive cost using waste heat sources originated in the cement production process.

As reported by the *International Finance Corporation (IFC),* waste heat recovery in the cement industry began in the 1980s and was mostly implemented in Asian companies. Today, the best-known technologies for this purpose range from classic conventional Rankine cycle (CRC) installations to organic Rankine cycles (ORC) and Kalina cycles. In still, there are more than 850 waste heat recovery systems installed in the world today, the vast majority of which are in China as (IFC, 2014).

Varma and Srinivas (2015) state that the total energy consumption for cement production in an average plant is approximately 5 GJ/ton, and 35% approximately of this amount is lost in the form of residual heat. The authors also emphasize the importance of reusing this significant amount of wasted energy. In order to harness this amount of energy, several studies have been carried out, for example, in their experimental study, Wang, H. et all (2015) evaluated environmental, economic indicators and performance parameters of a simple ORC basing its operation in a cement plant with clinker production capacity of 4,000 tons/day. The ORC in question could generate 6,785 to 8,121 MW of electricity per year, which would be equivalent to savings of 2,035 to 2,436 tons of fuel coal and a decrement of between 7,743 and

9,268 tons in $CO_2$ emissions. In another study Fergani, Touil and Morosuk (2016) modeled and performed a comparative analysis of economic, environmental and exergetic factors of a simple ORC working with three organic fluids (Cyclohexane, Benzene and Toluene) for residual heat recovery at a temperature of 350°C in the cement industry. The results showed that Cyclohexane was the fluid that obtained the highest performance from the perspective of exergetic efficiency, being 5.50% higher than Benzene and 33.45% to Toluene. Some important considerations can be drawn from several studies and studies reported in the literature, as mentioned as follow.

According to Fu, Lee and Hsieh (2015) the net power produced by ORC increases with the rise in temperature of the heat source. Long et all (2014) indicate that the thermodynamic properties of organic fluids have a direct impact on the exergetic performance of ORC and according to Li, X. et all (2014) for each working fluid there is a range of temperatures below the critical point at which it is possible to extract the maximum liquid power from the CRO. He et all (2012) indicate that organic fluid generates higher values of liquid power produced when their critical temperature is close to the temperature of the heat source. In this sense Wu, Zhu and Yu (2016) show that the temperature of the organic fluid during the phase change has a direct influence on the thermal efficiency of the ORC. Brown, Brignoli and Quine (2015) pointed out that simple hydrocarbon are more suitable for working in ORCs that have low temperature heat sources while complex hydrocarbons (siloxanes) are better suited to operate in CROs that have high temperature heat sources. Pu et all (2016) indicated that the expansion of the pressure variation between the turbine inlet and outlet makes it possible to increase the amount of net power generated by the CRO. Javanshir and Sarunac (2017) concluded that the thermal efficiency of CRO increases as fluid pressure at turbine inlet increases. However, for pressures greater than critical fluid pressure, thermal efficiency becomes independent of this parameter. As Imran et all (2014) to increase the temperature at the turbine inlet or Pinch Point in the evaporator and condenser collaborate to expand the thermal efficiency of the ORC. On the other hand, this cooperates for a considerable increase in the specific cost of the electricity production in the cycle. Gao et al. (2014) pointed out that the thermal efficiency of the subcritical ORC with overheating is higher than that of the same cycle in the subcritical operational condition. According to Meinel, Wieland and Spliethoff (2014) the ORC with saturator and simple steam extraction in the two-stage turbine is more efficient thermodynamically and economically when contrasted with simple cycles and cycles with regenerator. According to Li, Y. et all (2014) The higher the temperature of the heat source, the better the economic performance of the CRO.

In the next topic is presented the methodology to obtain the results of optimization of the electricity cogeneration with organic Rankine cycle (ORC) in cement industry with 3.500 ton of clink daily capacity in the Brazilian energy scenario as the main purpose of this work.

## 2. METHODOLOGY

This topic presents the ORC main methodology to obtain the optimization results of the electricity cogeneration in a cement industry with a daily production capacity of 3,500 t of clinker. Additionally, the equations for calculating the thermodynamic and economic indicators that allow the analysis of the optimization results, as well as the independent variables used and their variation ranges, are presented briefly. The methodology in detail can be found in Moreira (2018) and Moreira and Arrieta (2019).

### 2.1 Cement process data for electricity cogeneration

The two main sources of residual heat in a cement plant are the exhaust gas from the suspension preheater and the hot air discharge from the clinker cooler. These thermal sources have different temperatures, flow rates and chemical composition and can be used separately or combined for electricity production through cogeneration systems (WANG; DAI; GAO, 2009). Starting from this premise, the cycles in this work were designed to simultaneously use the thermal energy of both heat sources.

The input data regarding the exhaust gases of the cement production process were extracted from Apodi Cement (2015), a cement plant located in the city of Quixeré in the state of Ceará with a production capacity of 3,500 tons of clinker per day. Table 1 shows a summary of the input data of the gases of the cement production process that were used in the calculations.

Table 1 - Inlet data of the exhaust gases from manufacturing process of cement (Cimento Apodi, 2015).

| Variable | Unit | Value |
|---|---|---|
| Hot air from clinker cooler discharge molar composition: $N_2/O_2$ | % | 79.00/21.00 |
| Hot air from clinker cooler discharge Inlet temperature/Outlet temperature | ºC | 440.00/114.00 |
| Hot air from clinker cooler discharge mass flow rate | kg/s | 48.15 |
| Suspension preheater exhaust gas molar composition: $CO_2/N_2/O_2/\ H_2O$ | % | 26.30/64.58/4.94/4.18 |
| Suspension preheater exhaust gas Inlet temperature/ Outlet temperature | ºC | 310.00/228.00 |
| Suspension preheater exhaust gas mass flow rate | kg/s | 88.03 |
| | | |

## 2.2 Organic Rankine Cycle considered

The first proposed ORC configuration was simple, involving a single-stage turbine (TURB), a condenser (COND), a centrifugal pump (PP 01) and an evaporation unit, which consisted of an economizer (ECO), two evaporators (EVP 01 and EVP 02) and a superheater (SPH). An electric generator (GEN), an electrical substation (SEE) and an electric motor (M) for the centrifugal pump were also used. This simple ORC for waste heat recovery in cement plants is illustrated in Figure 1.

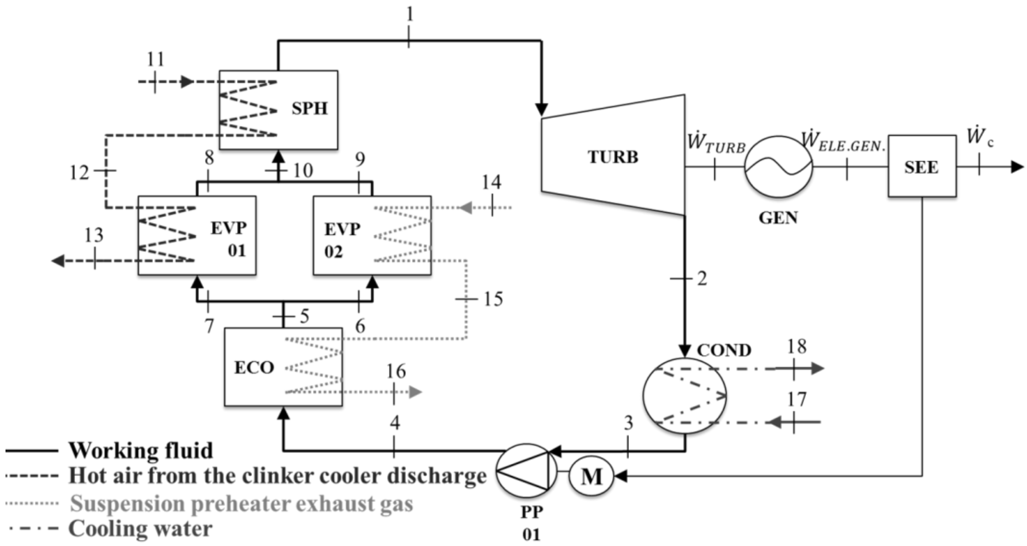


Figure 1. Simple ORC.

To increase the performance of the ORC some regenerative components were included in the system. These components can enhance the thermodynamic mean temperature of the organic fluid during the heat addition process and can reduce irreversible losses within the components of the cycle, increasing its overall effectiveness. This regenerative ORC is illustrated in Figure 1. The regenerative ORC configuration involved the same equipment as the simple arrangement, although other components were include in to the cycle, such as a regenerator (REG), a direct contact heater (DCH), a liquid drain trap (TRAP) and a second centrifugal pump (PP 02). The simple-stage turbine was also replaced by a multi-stage turbine with two steam extractions.

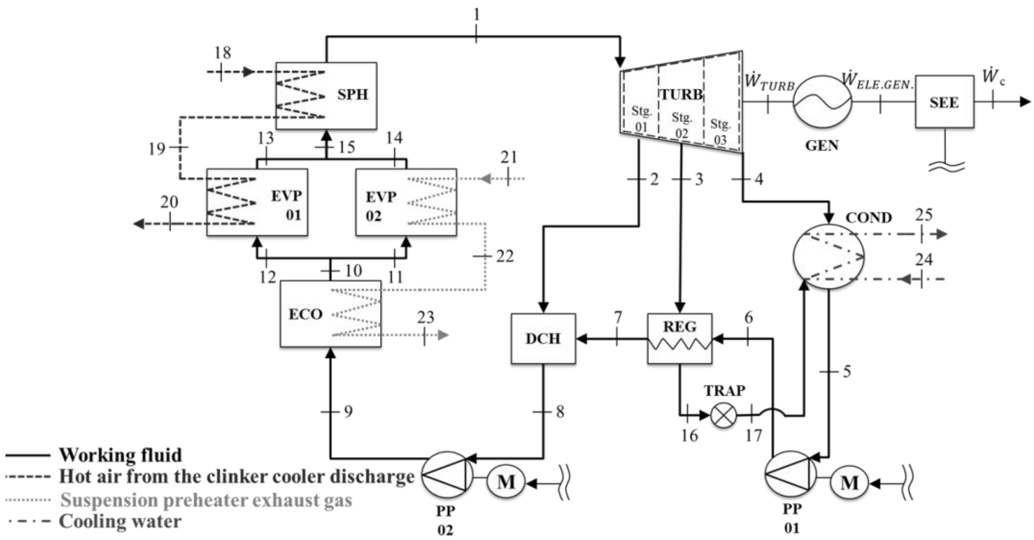


Figure 1. Regenerative ORC.

The two ORC configurations were modeled in the subcritical and subcritical conditions with overheating from the application of the first and second laws of thermodynamics in the components of the cycles to quantify the energetic and exergetic interactions.

## 2.3 Thermodynamic parameters

The indicators used for the analysis of results are the net power produced in the CRO, the exergetic efficiency, and the specific costs of generation and investment. The methodology for calculating the indicators is presented below.
The net power produced by the cycle is given by equation (1):

$$\dot{W}_c = \eta_{GEN} \cdot \dot{W}_{TURB} - \sum \dot{W}_{PP} \tag{1}$$

In which: $\dot{W}_c$ is the Net cycle power [kW], $\eta_{GEN}$ is the Electric generator efficiency, $\dot{W}_{TURB}$ is the Net turbine electric power [kW] and $\dot{W}_{PP}$ is the Pump power consumption [kW].

The exergetic efficiency of the cycle, for the simple ORC, is given by the equation (2):

$$\eta_{ex} = \left(\frac{\dot{W}_c}{\dot{m}_1 \cdot [h_1 - h_4 - T_0 \cdot (s_1 - s_4)]}\right) \cdot 100 \tag{2}$$

The exergetic efficiency of the cycle, for the regenerative ORC, is given by the equation (3):

$$\eta_{ex} = \left(\frac{\dot{W}_c}{\dot{m}_1 \cdot [h_1 - h_9 - T_0 \cdot (s_1 - s_9)]}\right) \cdot 100 \tag{3}$$

In the two previous equations: $\eta_{ex}$ is the ORC exergetic efficiency [%], $\dot{W}_c$ is the Net cycle power [kW], $\dot{m}_1$ - Steam mass flow at turbine inlet [kg/s], $h$ is the Specific enthalpy at the cycle states 1, 4 e 9 [kJ/kg], $s$ is the Specific entropy at the cycle states 1, 4 e 9 [kJ/kgK], $T_0$ is the Environment temperature [K].

Other input data such as the isentropic efficiencies of the pump and turbine were provided by Wang, Dai and Gao (2009). The other initial information assumed in the modeling, commonly used by several authors in this type of research, was obtained from the publications studied and include the pump isentropic efficiency (70%), turbine isentropic efficiency (85%), electric generator efficiency (98.5%), electric motor efficiency (99%), Pressure of the exhaust gases from cement production process (0.101 MPa), Environment pressure (0.101 MPa) and environment temperature (22°C).

## 2.4 Specific generation and investment cost

To obtain an order of magnitude regarding the expenses pertaining to an energy cogeneration project, the principles for cost estimation proposed by Ulrich and Vasudevan (2004) were applied to this work. This approach correlates, through graphs, the expenses generated by the components of the cycle with their main operational parameters such as power produced by the turbine, surface area of heat transfer of exchangers, power consumed by pumps, among others.
The specific cost of the investment, which is the relationship between the total cost of the investment and the net power generated by the CRO, can be calculated using the equation (4):

$$I = \frac{IT}{\dot{W}_c} \tag{4}$$

In which $I$ is the Specific investment cost [R$/kW] and $IT$ is the Total investment cost [R$].

The equation (5) allows obtaining the specific cost for electricity generation through the CRO considering the portions corresponding to the costs of investment, operation and maintenance of the system:

$$C = I\left(\frac{AF}{HO}\right) + CO\&M \tag{5}$$

In which: $C$ is the Specific cost for electricity production [R$/kWh], $AF$ is the Amortization factor [$year^{-1}$] computing considering an interest rate of 7%/year and a lifetime of 20 year; $HO$ is the Annual operating hours [adopted as 8030 h/year] and $CO\&M$ is the Specific cost of operation and maintenance [adopted as 0,02 R$/kWh]. The specific cost of electricity generated will be compared with the average electricity supply tariff for the industrial class practiced by Companhia Energética de Minas Gerais S.A. (CEMIG) in 2016 with the value of 0,4307 R$/kWh (DGSE, 2016). The calculation methodology of all cost and heat transfer in detail can be found in Moreira (2018) and Moreira and Arrieta (2019).

## 2.5 Optimization

At first, the optimization of the operational parameters of the investigated cycles was intended to find the maximum value of liquid power produced by them with the organic working fluids considered. Therefore, the maximization of the net power generated by the CROs was defined as an objective function in the first stage of optimizations. This parameter was also established as the main comparative criterion in this study. In addition, the results of other thermodynamic parameters linked to the power production of cycles such as heat supplied to the system, mass flow at turbine inlet, exergy destroyed in ORC and thermal and exergetic efficiencies were also analyzed. Andin a second moment, the net power results found in the optimizations were compared to the results obtained during the simulations of the cycles to evidence the beneficial effect of working with optimized operational parameters. This first stage of optimizations was finalized with the appreciation of the results of economic modeling.

Subsequently, other operational parameters were also optimized to verify their impact on ORC performance and each other's results. For this reason, maximizing exergetic efficiency and minimizing specific costs of investment and electricity generation were also defined as an objective function in the second phase of optimizations. The reason why the maximization of exergetic efficiency was chosen as an objective function in this stage of optimizations is justified by the fact that this parameter and the net power produced by the cycles are the ones that best represent the thermodynamic performance of the ORCs because they contemplate both the power supplied for final consumption, and the performance of the system considering the losses per action of irreversibility. On the other hand, the minimization of the specific costs of the investment and for electricity generation were also chosen as an objective function because they better portray the economic modeling performed due to the inclusion of very important parameters such as net power produced by the cycles, total cost of investment and other relevant costs that are applied in practice.

Regarding the operational parameters, the simple and regenerative cycles were optimized in the subcritical operational condition, modifying the temperature difference between the entry of organic fluid into evaporator 02 and the output of exhaust gases in the equipment. Another optimized parameter was the subcooling temperature in the economizer. Then, the cycles were optimized in the under critical operation condition with overheating using the same procedure employed in the subcritical condition. However, the temperature difference between the organic working fluid outlet and the inlet of exhaust gases in evaporator 01 was also varied, as well as the temperature at the turbine inlet from the temperature at the optimum operating pressure determined in the simulation of the ideal CRO to a temperature 10°C lower than the hot air discharge temperature of the clinker cooler at the superheater inlet. This logic was adopted in the optimization of liquid power and other operating parameters. Therefore, all optimizations had the same variation intervals of the operation parameters and restrictions applied to the ORC, changing only the objective function depending on the focus of the analysis.

It should be noted that the temperature ranges studied were specified in order to provide the convergence of calculations during the optimizations of the cycles and ensure that the exhaust gas temperatures at the outputs of evaporators 01 and 02 were higher than the minimum limits extracted from Apodi Cement (2015) that were shown in Table 1. Furthermore, the pressure ratios in turbine extractions in regenerative cycles were kept constant at values specified according to the fluid under analysis to enable the correct functioning of this configuration in both operational conditions examined. Table 2 shows the variation intervals of the operating parameters during optimization.

Finally, Table 3 summarizes the information about the parameters considered during the execution of optimizations by genetic algorithm and the restrictions applied to cycles. The genetic algorithm method presents in the EES library, which is derived from the Pikaia program (V.1.02, 2002) of public domain written by Paul Charbonneau and Barry Knapp, was used to optimize the variables mentioned.

Table 2 – Range of variation of the operating parameters for the designed ORCs.

| Fluid | Both configurations | | | Simple ORC | Regenerative ORC | | |
|---|---|---|---|---|---|---|---|
| | $\boldsymbol{\Delta T_{EVP\,02}}$ min - máx [°C] | $\boldsymbol{\Delta T_{EVP\,01}}$ (1) min - máx [°C] | $\boldsymbol{T_1}$ (1) min - máx [°C] | $\boldsymbol{\Delta T_{sub-cooling}}$ min - máx [°C] | $\boldsymbol{\Delta T_{sub-cooling}}$ min - máx [°C] | $\boldsymbol{P_2/P_1}$ [-] | $\boldsymbol{P_3/P_1}$ [-] |
| R11 | 100 - 200 | 100 - 200 | $T_1$ at $P_{1,opt}$ - 430 | 71 - 139 | 31 - 66 | 0.25 | 0.10 |
| R123 | | | | 111 - 130 | 44 - 67 | 0.25 | 0.15 |
| R141b | | | | 97 - 139 | 45 - 67 | 0.25 | 0.10 |

(1) These operating parameters were optimised in the subcritical condition with superheating only.

Table 3 Optimization parameters and constraints.

| Variable | Unit | Value |
|---|---|---|
| Optimization parameters used in the genetic algorithm method: | | |
| Number of generations | - | 64 |
| Number of individuals | - | 32 |
| Maximum mutation rate | - | 0.2625 |
| Constraints to the designed ORCs: | | |
| Entropy generation within each component | kW | ≥ 0 |
| Exergy destruction within each equipment | kW | ≥ 0 |
| Hot air temperature at the evaporation unit outlet (1) | °C | ≥ 114.00 |
| Suspension preheater exhaust gas temperature at the evaporation unit outlet (2) | °C | ≥ 228.00 |

(1) Typical process temperature at the evaporation unit outlet.

(2) The value of 228 °C is an acceptable temperature in Brazilian cement plants for drying the raw material before its inlet into the suspension preheater.

## 3. RESULTS AND DISCUSIONS

The results are presented and confronted in the target charts of Figures 3 (for R141b), 4 (for R11) and 5 (for R123) throughout this section. The values collected in the net power optimizations are represented by circles (●), the optimized results of exergetic efficiency are symbolized by crosses (✚), the values of the optimizations of the specific investment cost are characterized by squares (■) and the optimized results of the specific electricity generation cost are indicated by triangles (▲). The letters (a), (b), (c) and (d) correspond to the arrangement of simple subcritical, simple subcritical cycles with superheating, subcritical regenerative and regenerative subcritical with superheating, in this order.

For a better interpretation of the target charts, the axes should be analyzed clockwise: (i) on the upper vertical axis the results pertaining to the net power generated are demonstrated; (ii) in the right intermediate axis, the values of exergetic efficiency are had; (iii) on the lower vertical axis, the specific investment cost results are displayed; (iv) on the left intermediate axis, the specific electricity generation cost values are provided. Moreover, the intersection point of the four axes is equivalent to the minimum value of each scale and they are in ascending order from this point to the ends of the circles.

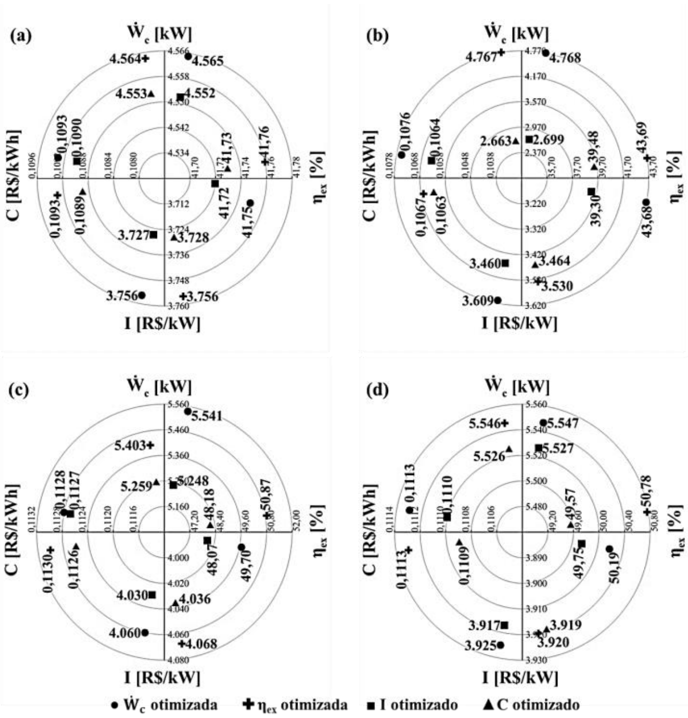


Figure 3 - Comparison of simple and regenerative CRO optimizations in subcritical and subcritical conditions with superheating for R141b

First, when a thoroughly ascertaining the results obtained, it was verified that the optimization of one parameter exerted a direct influence on the results of the others. Applying as a comparative factor the results found in the net power optimizations, it was observed that the maximization of the exergetic efficiency promoted the increase of this indicator both in the subcritical and subcritical simple ORCs with superheating, as well as in the regenerative ORCs in these same operating conditions in an average of 0.02%, 0.21%, 0.90% and 1.32%, respectively. These increases in the values of exergetic efficiency are mainly attributed to the decline of the portion of exergetic input transferred to the cycles during the evaporation stages of the working fluid. This decrease, in turn, occurred due to the increase in the flow values of exhaust gases at the outlet of the evaporation unit. This provided less variation in the exergetic flow of gases from the cement production process in this component and lower inlet of exergy consumed by the system. Also, the decrease in the destruction of exergy in the equipment of the cycles due to the reduction of losses due to the action of irreversibility in them was another factor that influenced for this result.

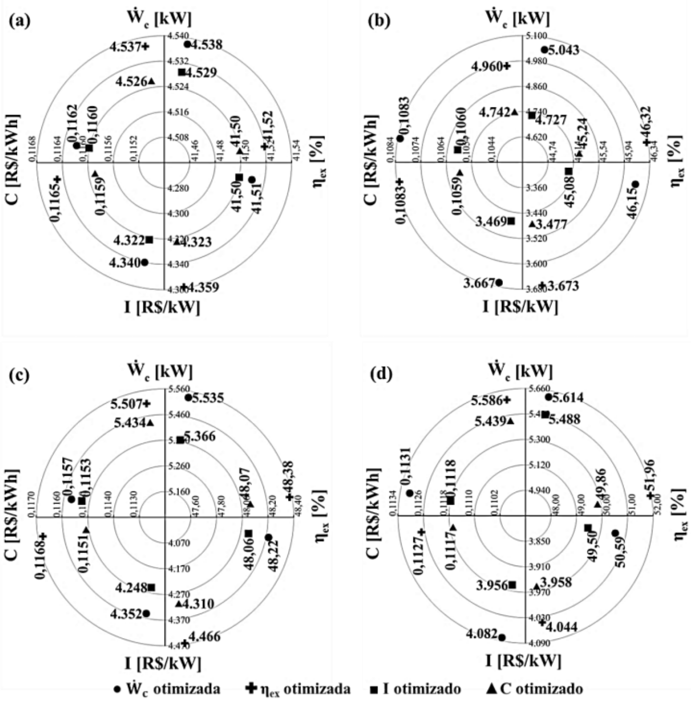


Figure 4 - Comparison of simple and regenerative CRO optimizations in subcritical and subcritical conditions with superheating for R11

However, it was observed that the growth of the exergetic efficiency of the ORCs caused average decrements in the net power production of 0.03%, 0.72%, 1.01% and 0.27% in the simple subcritical and subcritical configurations with superheating, as well as in the subcritical and subcritical regenerative arrangements with superheating, in this order. This fact is justified by the decrease in the value of the product between the mass flow of the organic fluid that was minimized and the enthalpy difference in the turbine that remained stagnant. However, although the net power generation of the cycles has decreased, the decline in the amount of exergetic input provided to the systems was the decisive factor that allowed the increase in its exergetic efficiency.

Moreover, during the optimization of the exergetic efficiency of the ORCs, it was also noticed that the indicators related to costs experienced increases. The specific costs of investment both of the simple configurations in the subcritical and subcritical conditions with superheating, as well as of the subcritical and subcritical regenerative cycles with superheating reached average increases of 0.18%, 0.24%, 0.25% and 0.31%, respectively. From the perspective of the specific electricity generation cost, these average increases were 0.09%, 0.25%, 0.14% and 0.13% for the respective ORCs and operating conditions cited. Although the expansion in the costs of the studied systems did not reach an order of magnitude that was too significant, these increases occurred due to the decrease in the average temperature in the heat inlet process in the evaporation stages of the work fluids together with the decrease in their mass flow, which required the exchangers to have a greater surface area of heat transfer. Therefore, there was an increase in costs with these components, since they had larger dimensions.

Therefore, the optimization of the exergetic efficiency of the proposed ORCs revealed that it is possible to obtain discrete gains about this parameter to the detriment of the net power generated by the cycle and the expansion of costs related to it. For this reason, it should be carefully evaluated, based on the type of application, whether the modest improvement in the exergetic efficiency of the system would compensate for the reduction in the level of net power produced and the worsening in the financial indicators of the CRO, even in small proportions.

From the economic perspective, it was evidenced that by minimizing both cost indicators, the net power generated by the cycles also suffered decrement. This is explained by the fact that in addition to the variation of enthalpy in the turbine having experienced reduction, the mass flow of organic fluid at the entrance of the equipment also declined. Furthermore, it was also found that there was a decay in the exergetic efficiency of the cycles during optimizations. This fact occurred because, although there was an increase in the levels of exergy flow of exhaust gases at the outlet of the evaporation unit, which decreased the amount of exergy inlet supplied to the ORCs, this condition was suppressed by the decrease in the production of liquid power as mentioned. This made the cycles less efficient from the perspective of exergetic efficiency. Another finding in the context of economic indicators is that the lower mass flow value of the work fluid in the system made possible by the optimization of specific investment costs and for the generation of electricity provided the cycles with a less robust and costly components, producing a positive impact on the results relevant to the costs of the ORCs. An elucidative example of this fact was observed in the costs of heat exchangers, which are the most pronounced of cycles. The reductions in the average thermodynamic temperatures of the organic fluids in the heat intake process thanks to the lower portion of steam generated promoted a minimization in the surface area of heat transfer necessary for the evaporation of the same and, consequently, the expenses with these equipment were lower.

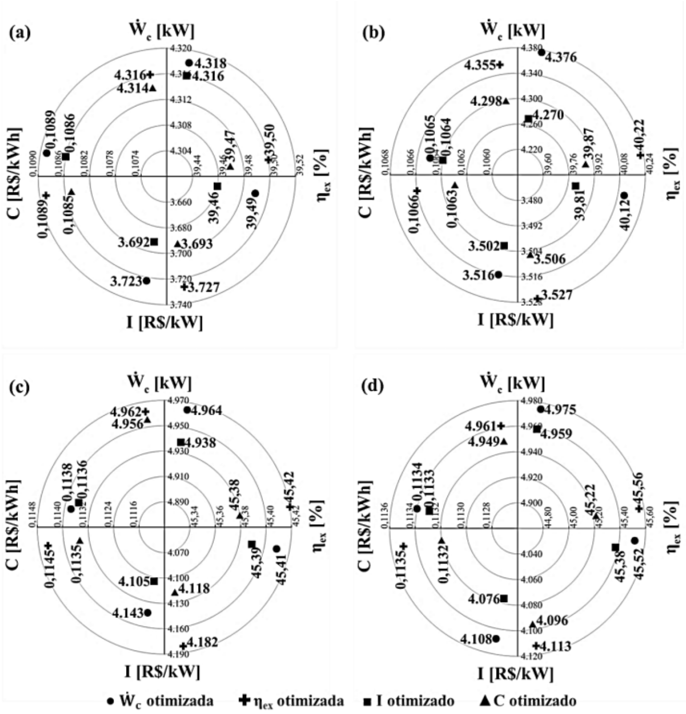


Figure 5 - Comparison of simple and regenerative CRO optimizations in subcritical and subcritical conditions with superheating for R123

Thus, the average decrements in the specific investment cost of subcritical and subcritical simple ORCs with superheating and regenerative in these same operating conditions amounted to 0.67%, 3.31%, 1.35% and 1.36%, in this order. However, the optimization of this parameter caused a decrease in the levels of net power produced compared to the results obtained in the optimization of this same magnitude in section 5.3, on average, of 0.18%, 4.34%, 2.95% and 0.98% in the simple subcritical and subcritical configurations with overheating, as well as in subcritical and subcritical regenerative arrangements with superheating, respectively. Also, the average decrement in exergetic efficiency for the mentioned compositions was 0.06%, 1.55%, 1.22% and 1.11%, in this order. Moreover, the results of the specific cost for electricity generation also followed the behavior pattern of the other parameters. The reductions in this indicator were, on average, 0.24% for the subcritical simple cycle, 1.11% for the subcritical simple ORC with overheating, 0.20% for the subcritical regenerative arrangement and 0.50% for the subcritical regenerative configuration with superheating.

On the other hand, the search for optimal values regarding the specific electricity generation cost provided the cycles with an average decline in the results of this parameter of 0.33%, 1.20%, 0.32% and 0.59% in the simple subcritical and subcritical configuration with superheating and also in the subcritical and subcritical regenerative cycles with superheating, respectively. However, the optimization of this indicator generated an average decay in the value of net power produced of 0.21% in the simple CRO, 3.88% in the simple subcritical ORC with superheating, 2.36% in the subcritical regenerative configuration and 1.34% in the subcritical regenerative arrangement with superheating. In addition, the average decreases in exergetic efficiency for the cited compositions were equal to 0.04%, 1.30%, 1.15% and 1.11%, in this order. Average decreases of 0.65%, 3.16%, 0.72% and 1.16% were also observed in the values of the specific cost of the investment for the respective cycles mentioned.

Another aspect observed during the optimizations of the economic indicators of the designed cycles was the proximity between the results obtained in minimizing the specific investment cost and specific electricity generation cost. This relatively small difference between the results of each indicator is attributed to the correlation between these two parameters. Therefore, when one of these indicators is modified, the other also experiences changes in the same order of magnitude, but indirectly.

Moreover, the work fluids that stood out from the financial point of view with lower values related to the specific investment cost and specific electricity generation cost were the fluids R141b and R11, respectively, both in the simple subcritical CRO with superheating. In the first case, when the reduction of the specific cost of the investment was determined as an objective function, the isentropic fluid R141b achieved a result 11.82% lower than the mean value found in the other optimizations of this parameter. Also, this result was lower in 0.73% when contrasted to the average value of the other fluids working in this configuration and operating condition.

In the second case, where optimization was performed to obtain the lowest possible value of specific cost for electricity generation, the isentropic fluid R11 reached a result 4.80% below the average level of the other optimizations for this indicator. This amount was also 0.38% lower compared to the average value of the other fluids in the same optimization circumstances. Thus, it was noticed that the results of economic indicators are associated with the decrement in the values related to the net power produced by the cycles and the total cost of the investment, which in turn suffered a reduction in its value due to the reduction of costs as established in the objective function of the genetic algorithm.

## 4. CONCLUSIONS

The technical-economic analysis of organic Rankine cycles for cogeneration in the cement industry allows to realize the following conclusions:

- The regenerative configuration as expected showed better indicators of thermodynamic performance when compared to the simple cycle.
- From the thermodynamic point of view, R141b fluid proved to be more attractive for applications without superheating with net power generation in the range of 4,565 kW to 5,541 kW, with exergetic efficiency between 41.75% and 49.70%. With superheating, the R11 fluid was more attractive with generation of liquid power generated with 5,043 kW and 5,614 kW, and exergetic efficiency between 46.15% and 50.59%.
- From the economic point of view, fluid R123 was more attractive with the lowest specific cost values of the investment (3.516 R$/kW) and the specific electricity generation cost (0.1065 R$/kWh) in the configuration of subcritical simple cycle with superheating. Investment specific cost values of 3,723 R$/kW and specific electricity generation cost of 0.1089 R$/kWh were obtained with R123 in the simple cycle configuration without superheating.
- From the results obtained it can be affirmed that, among the studied fluids, R141b becomes the most attractive for cogeneration in the cement industry because it presents the best thermodynamic performance without losing much economic competitiveness when compared to the economic results shown by R123.
- Through the ORCs investigated in this study, it would theoretically be possible to supply between 9.59% and 18.71% of the electricity demand contracted by the cement plant Apodi.

## 5. ACKNOWLEDGEMENTS

This work was supported in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Brasil (CAPES) [Finance Code 001]; the Pontifical Catholic University of Minas Gerais (PUC Minas); and FAPEMIG [research project PPM-00381-16].

## 6. REFERENCES

Brown, J. S., Brignoli, R., Quine, T., 2015. “Parametric investigation of working fluids for organic Rankine cycle applications”. *Applied Thermal Engineering*. Vol. 90, No 1, pp. 64-74.

Cimento APODI., 2015. “Companhia Industrial de Cimento Apodi. Waste heat recovery system”. Quixeré, CE, 15 slides: color.

DEPARTAMENTO DE GESTÃO DO SETOR ELÉTRICO - DGSE., 2017 “Informativo tarifário”. 31 ago. 2017 < http://www.mme.gov.br/web/guest/secretarias/energia-eletrica/publicacoes/informativo-tarifario-de-energia-eletrica>.

EMPRESA DE PESQUISA ENERGÉTICA - EPE., 2016. “Balanço Energético Nacional”. 12 set. 2016. <https://ben.epe.gov.br/downloads/Relatorio_Final_BEN_2016.pdf>.

Fergani, Z., Touil, D., Morosuk, T., 2016. “Multi-criteria exergy based optimization of an Organic Rankine Cycle for waste heat recovery in the cement industry”. *Energy Conversion and Management*, Vol. 112, No. 1, pp. 81-90.

Fu, B., Lee, Y., Hsieh, J., 2015. "Design, construction, and preliminary results of a 250-kW organic Rankine cycle system". *Applied Thermal Engineering*. Vol. 80, No 1, pp. 339-346.

Gao, W., et al., 2014. "Working fluid selection and preliminary design of a solar organic Rankine cycle system". *Environmental Progress & Sustainable Energy*. Vol. 34, No 2, pp. 619-626.

He, C., et al., 2012. "The optimal evaporation temperature and working fluids for subcritical organic Rankine cycle". *Energy*. Vol. 38, No 1, pp. 136-143.

Imran, M., et al., 2014. "Thermo-economic optimization of Regenerative Organic Rankine Cycle for waste heat recovery applications". *Energy Conversion and Management*. Vol. 87, No 1, pp. 107-118.

Incropera, F.P. and Dewitt, D.P., *Fundamentals of heat and mass transfer*. John Wiley & Sons, New York, 4th edition.

INTERNATIONAL FINANCE CORPORATION - IFC., 2017. "Waste heat recovery for the cement sector: Market and Supplier Analysis. Washington". 12 jan. 2017 < http://www.ifc.org/wps/wcm/connect/topics_ext_content/ifc_external_corporate_site/ifc+sustainability/learning+and+adapting/knowledge+products/publications/report_waste_heat_recovery_for_the_cement_sector_market_and_supplier_analysis>.

Javanshir, A., Sarunac, N., 2017. "Thermodynamic analysis of a simple Organic Rankine Cycle". *Energy*. Vol. 118, No 1, pp. 85-96.

KALEX, LLC., 2010. "Kalina cycle power systems for cement kiln waste heat applications". 09 dez. 2017 <http://kalexsystems.com/KalexCementWasteHeatBrochure10-10.pdf>.

Li, X., et al., 2014. "Working fluid selection based on critical temperature and water temperature in organic Rankine cycle". *Science China Technological Sciences*. Vol. 58, No 1, pp. 138-146.

Li, Y., et al., 2014. "Economical evaluation and optimization of subcritical organic Rankine cycle based on temperature matching analysis". *Energy*. Vol. 68, No 1, pp. 238-247.

Long, R., et al., 2014. "Exergy analysis and working fluid selection of organic Rankine cycle for low grade waste heat recovery". *Energy*. Vol. 73, No 1, pp. 475-483.

Meinel, D., Wieland, C., Spliethoff, H., 2014. "Economic comparison of ORC (Organic Rankine cycle) processes at different scales". *Energy*. Vol. 74, No 1, pp. 694-706.

Moreira, L. F., Arrieta, F. R. P., 2019. "Thermal and economic assessment of organic Rankine cycles for waste heat recovery in cement plants. *Renewable & Sustainable Energy Reviews*. Vol. 114, No 1, p. 109315.

MOREIRA, L.F., 2018. *Análise técnico-econômica de ciclos Rankine orgânicos para cogeração na indústria de cimento*. MSc. Dissertation, Pontifícia Universidade Católica de Minas Gerais, Belo Horizonte, Brasil.

Pu, W., et al., 2016. "Experimental study on Organic Rankine cycle for low grade thermal energy recovery". *Applied Thermal Engineering*. Vol. 94, No 1, pp. 221-227.

Ulrich, G.D. and Vasudevan, P.T., 2004. *Chemical engineering process design and economics: a practical guide.* Durham: Process Publishing, 2nd edition.

Varma, G. V., Pradeep, Srinivas, T., 2015. "Design and analysis of a cogeneration plant using heat recovery of a cement factory". *Case Studies in Thermal Engineering*. Vol. 5, No 1, pp. 24-31.

Wang, H., et al., 2015. "Organic Rankine cycle saves energy and reduces gas emissions for cement production". *Energy*. Vol. 86, No 1, pp. 59-73.

Wang, J., Dai, Y., Gao, L., 2009. "Exergy analyses and parametric optimizations for different cogeneration power plants in cement industry". *Applied Energy*. Vol. 86, No 6, pp. 941-948.

Wu, Y., Zhu, Y., Yu, L., 2016. "Thermal and economic performance analysis of zeotropic mixtures for Organic Rankine Cycles". *Applied Thermal Engineering*. Vol. 96, No 1, pp. 57-63.

## 7. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.