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**STUDY OF ZEOTROPIC MIXTURES FOR COGENERATION  
IN THE CEMENT INDUSTRY**

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**Abstract.** This work aimed to study energy cogeneration through the Regenerative Organic Rankine Cycle (ORC) for waste heat recovery in cement industry using zeotropic mixtures as working fluid. In addition, an ideal simple ORC was also modeled in order to choose the molar fraction of each mixture and their performance in the cycle. After modeling the cycles, some operating parameters of the ORCs were optimized with the maximization of the net power as an objective function. The zeotropic mixtures properties were used from the REFPROP software database, the models were calculated using the Engineering Equation Solver (EES) software and the optimizations, performed in the same program, employed the conjugated direction method. The results of the ideal ORC showed that the MM/MDM mixture, at a molar fraction of 0,1/0,9, obtained the greatest power production. However, this mixture had a lower pressure at the condenser outlet than the atmospheric pressure, so it would be necessary to make a vacuum in the condenser and the total cost of the system would increase, therefore, this mixture was rejected from the study. The mixtures selected for the study were R227ea/R245fa, MDM/R134a, MD2M/R134a and D4/R134a, the molar fraction proportions chosen were 0,1/0,9, 0,44/0,56, 0,345/0,655 and 0,378/0,622, respectively. In the optimizations results, it was found that the average superiority of the regenerative cycle operating with the R227ea/R245fa mixture, in terms of net power, was around 31.9%, 31.8% and 49.0% when comparing with the other mixtures MDM/R134a, MD2M/R134a and D4/R134a, in that order. From an economic perspective, the highest cost for the production of electricity among the mixtures studied was 41.32% lower than the electricity sale price practiced by the local energy concessionaire.

**Keywords:** Regenerative Organic Rankine cycle, zeotropic mixtures, conjugate direction method.

## 1. INTRODUCTION

Global warming, a worldwide problem still under study by the scientific community, is caused by emissions of polluting gases resulting from industrial processes with consumption and generation of thermal and electrical energy. The growth of the greenhouse effect causes new technologies and methodologies to be developed to reduce and control emissions in industries resulting from energy consumption. Ensuring the combination of the best environmental practices in production processes such as cement manufacturing using efficiently thermal and electrical energy has become desirable in order to reduce the greenhouse effect. The technology of the Organic Rankine Cycle (ORC) has been developing and has proved to be interesting for several industrial processes, due to the good use of low thermal energy sources, such as residual heat (HANZHI, 2017). Therefore, it is necessary to determine the appropriate working fluid for the application of an ORC, taking into account the temperature of the heat source, the efficiency of the fluid for systems under certain conditions, fluid properties, environmental impacts, type of mixture and other factors inherent to the process.

Among the working fluids, zeotropic mixtures have some advantages, since it can be used under lower temperature and evaporation pressure. Therefore, the analysis of the feasibility of the cogeneration system using zeotropic mixtures in the ORC can enable significant gains in the cement manufacturing process such as greater efficiency and more competitiveness in the market, in addition to reducing environmental impacts and fuel consumption. The present work aims to continue Moreira and Arrieta (2019) study, performing analysis of the regenerative ORC, using zeotropic mixtures as the working fluid.

## 2. METHODS AND DATA

The following section describes the methodology for the selection of organic working fluids, the specifications of the regenerative ORC and their thermodynamic and economic model.

## 2.1 Conceptualization of mixtures as a working fluid

As cited by Wang et al. (2018), zeotropic mixtures can effectively reduce the irreversibility of heat transfer between working fluids and heat sources or heatsinks for thermodynamic systems. This is due to the characteristic of the zeotropic mixture having temperature variation during boiling and condensation. A mixture is called zeotropic when the composition of the vapor and liquid are not constant during the changing phase for a given pressure, as shown in Figure 1, in which the limits A, B, C and D define the saturated vapor line and the K point defines the two-phase region of the zeotropic mixture. Therefore, a difference between the saturation temperatures of the liquid and the vapor occurs in the process, this temperature difference is known as the temperature glide. Thus, when the working fluid used is a zeotropic mixture, it is expected that the performance of the power generation system will increase, since as greater the temperature difference between the heat source and the heatsink is, the greater the thermal efficiency of the cycle according to the laws of thermodynamics will be. Zhai et al. (2018) added by stating that zeotropic mixtures increase the performance of the ORC not only because the mixtures decrease the loss of exergy in the evaporator and condenser of the system, but also because they increase the rate use of heat source.

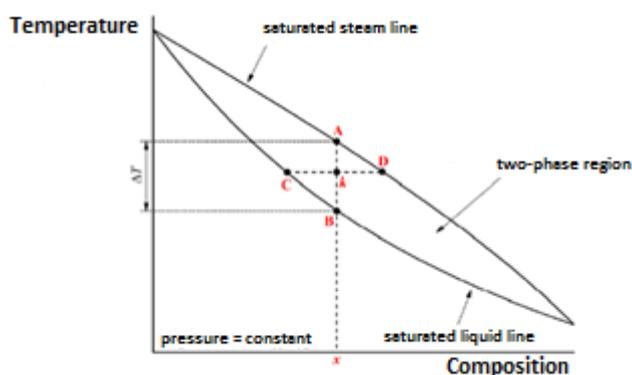


Figure 1. Schematic diagram of temperature and composition for a binary zeotropic mixture at constant pressure.  
 Available from: Modi, 2017

The selection of working fluids for this research was based on scientific publications. In most cases, these studies present a comparison between a set of candidates working fluids in terms of thermodynamic performance and based on a thermodynamic model of the cycle. In addition, the Montreal Protocol was also respected, which determines the decrease of substances that deplete the ozone layer. All HCFCs (hydrochlorofluorocarbons) that are under import control, or Controlled Substances (CS), mixtures containing HCFCs and all substances contained in the Decision XIX/6 of the Montreal Protocol will not be analyzed in this work, since the objective is to use a mixture zeotropic 100% viable to the environment and efficient to the employed system. As the selection of fluids became restricted after the elimination of all those that would be banned until 2030 in Decision XIX/6 of the Montreal Protocol, some other fluids were investigated in order to increase the range of mixtures to be studied in the present work. Siloxanes and hydrofluorolefins (HFOs) are the groups of these fluids.

Siloxanes are a class of fluids composed of molecules containing alternating atoms of silicon and oxygen in a linear or cyclic arrangement, usually with two or three organic groups attached to the silicon atom and it has excellent thermal stability with the Ozone Layer Destruction Potential (ODP) equals to zero and low global warming potential (GWP) (TIAN, 2017). Table 1 presents the final pure fluids that will be mixed in order to create a more suitable zeotropic mixture for the ORC in order to increase the efficiency of the cycle.

Table 1. Organic working fluids selected for application in this study.

Group	Working Fluid	Security Level	ODP	GWP	Classification	Environmentally viable
Hydrofluorocarbons	R-123	B1	0,020	77	Dry	Discarded
	R-124	A1	0,022	609	Isentropic	Discarded
	R-134a	A1	0,000	1.430	Wet	x
	R-143a	A2	0,000	4.470	Wet	x
	R-218	A1	0,000	8.830	Discarded	Discarded

	R-227ea	A1	0,000	3.220	Dry	x
	R-245fa	B1	0,000	1.030	Dry	x
	R-C318	A1	0,000	10.300	Discarted	Discarted
	R-290	A3	0,000	~20	Wet	x
	R-600a	A3	0,000	~20	Isentropic	x
Siloxanes	D4	A3	0,000	~0	-	x
	D5	A3	0,000	~0	-	x
	MM	A3	0,000	~0	-	x
	MDM	A3	0,000	~0	-	x
	MD2M	A3	0,000	~0	-	x
HFO	DR-2	A1	0,000	2	-	x
	DR-12	A1	0,000	32	-	x

Em vista das referências bibliográficas apresentadas e da seleção dos fluidos apresentada as misturas que serão formadas e utilizadas como fluidos de trabalho para o ORC Regenerativo abordado são: R227ea/R245fa, MM/MDM, MDM/R134a, MD2M/R134a e D4/R134a.

## 2.2 ORC specifications

The modeling of the cycle in this work was similar to a real one in a cement industry, so the configuration tended to take advantage simultaneously of two heat sources of a cement factory: the exhaust gas from the suspension preheater and the discharge of hot air from the clinker cooler. The composition of the Regenerative ORC, represented in Figure 2, was made using the condenser (COND), the three-stage turbine (TURB) with two steam extractions to the regenerator (REG) and the direct contact heater (DCH), the liquid drain trap (TRAP), the centrifugal pump (PP 01), another centrifugal pump (PP 02) and the evaporation unit, subdivided into economizer (ECO), superheater (SPH), evaporator 01 (EVP 01) and evaporator 02 (EVP 02), this division was made to take advantage of the residual heat. A power source and an electric pump motor were also added to the cycle, since this is a cement production process, which are: an electrical energy generator (GEN) and an electrical energy substation (SEE).

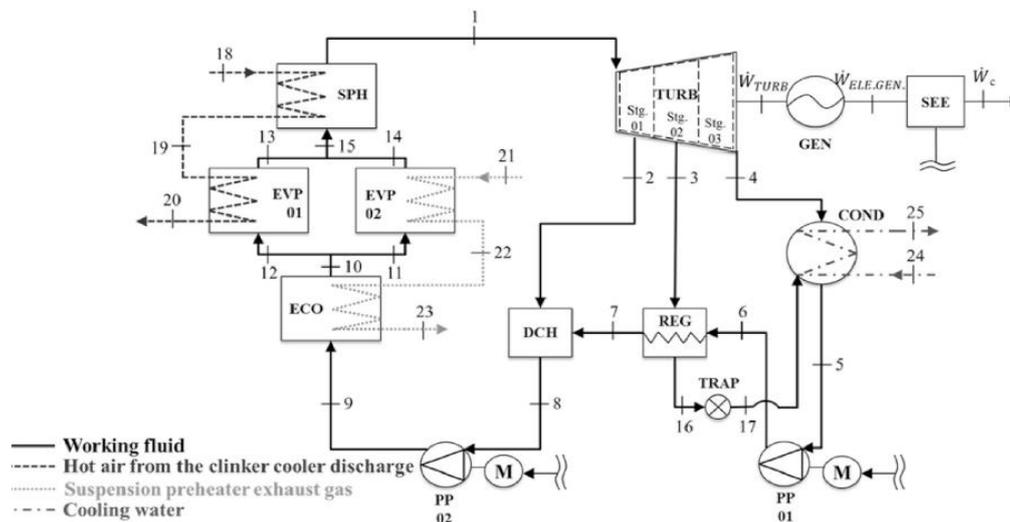


Figure 2. Regenerative ORC for Waste Heat Recovery (WHR) in cement industry.  
Available from: Adapted from Moreira e Arrieta, 2019

## 2.3 Energy data from cement plants

It was defined by Moreira and Arrieta (2019) that the condenser works as a hull-type heat exchanger and single-pass tubes with countercurrent flow and the non-finned cross-flow configuration was adopted for the other heat exchangers in the arrangement of the ORC. The global heat transfer coefficients were also provided by Moreira and Arrieta (2019) and applied to the modeling of exchanges according to the types of fluids and the interaction between their physical states. As the main focus of the work is the use of zeotropic mixtures, it is notable that when varying the composition of the mixture,

the value of the overall heat transfer coefficient (U) would also be variable. However, as an insufficient constructive information about the project wasn't obtained, such as length and diameter of the pipes, number and types of fittings in the networks, etc., as it's not possible to estimate the volume of fluid required, the value of U was considered a constant.

Taking this regenerative ORC as the system to be used, considering that the working fluid will be zeotropic mixtures with the selected refrigerants, the thermodynamic modeling will be done from the following input data presented by Moreira and Arrieta (2019). The input data for the exhaust gases from the cement production process were extracted from Cimento Apodi (2015), a cement factory located in the city of Quixeré in the state of Ceará – Brazil with a production capacity of 3,500 tons of clinker per day. The other input data, such as the pump and turbine isentropic efficiencies, were provided by Wang, Dai and Gao (2009). The initial information assumed in the modeling, commonly used by Moreira and Arrieta (2019) and several other authors, were obtained from the publications studied. Equipment efficiencies, as well as other initial data, were also extracted as presented by Moreira and Arrieta (2019). The properties of the refrigerant fluids were extracted from the database of both *REFPROP* and *EES* software. The thermodynamic modeling was done exclusively by the *EES* software.

## 2.4 Thermodynamic modeling

The ORC was modeled in the *EES* software (v.10.092) using mass balance and the first and second laws of thermodynamics. Each component was evaluated as a control volume and it was also established that the variation in kinetics and potential energies were insignificant, the control volumes were in a steady state, all the processes were adiabatic and the exhaust gases from the suspension preheater and the hot air from the discharge of the clinker cooler behaved as ideal gases.

The main equations of the thermodynamic model of the regenerative ORC are presented below. The equations for each process originate from the conservation mass law and the conservation energy law, which can be demonstrated in equations (1) and (2):

$$\frac{dm_{vc}}{dt} = \sum_e \dot{m}_e - \sum_s \dot{m}_s \quad (1)$$

$$\frac{dE_{vc}}{dt} = \dot{Q}_{vc} - \dot{W}_{vc} + \sum_e \dot{m}_e \left( h_e + \frac{1}{2} V_e^2 + g z_e \right) - \sum_s \dot{m}_s \left( h_s + \frac{1}{2} V_s^2 + g z_s \right) \quad (2)$$

The thermal efficiency of the ORC is measured by the amount of energy supplied for the working fluid that goes through the boiler. Equation (3) defines the thermal efficiency:

$$\eta = \frac{\dot{W}_t / \dot{m} - \dot{W}_b / \dot{m}}{\dot{Q}_{ent} / \dot{m}} \quad (3)$$

The entropy variation, second law of thermodynamics, which quantifies the irreversibilities of thermodynamic processes is given by equation (4):

$$\frac{dS_{vc}}{dt} = \sum_i \frac{\dot{Q}_i}{T_i} + \sum_e \dot{m}_e s_e - \sum_s \dot{m}_s s_s + \dot{\sigma}_{ger} \quad (4)$$

The isentropic efficiencies of the turbine and pump are provided by equations (5) and (6), respectively:

$$\eta_{TURB} = \left( \frac{\dot{W}_{real}}{\dot{W}_{ideal}} \right) \cdot 100 \quad (5)$$

$$\eta_{PP} = \left( \frac{\dot{W}_{ideal}}{\dot{W}_{real}} \right) \cdot 100 = \left[ \frac{(h_{ss} - h_e)}{(h_s - h_e)} \right] \cdot 100 \quad (6)$$

By definition, exergy is the maximum theoretical work possible to be acquired from a global system, composed of a system and the environment, coming into balance with the dead state, that is, being at rest in relation to the environment (MORAN, 2011). The use of exergy in this study is applied to control volumes on a permanent basis, that is, with no variation over time. Therefore, the balance of the exergy rate can be defined by equation (7):

$$\frac{d\dot{E}x_{vc}}{dt} = \sum_i \left( 1 - \frac{T_0}{T_i} \right) \dot{Q}_i - \left( \dot{W}_{vc} - P_0 \frac{dV_{vc}}{dt} \right) + \sum_e \dot{m}_e ex_e - \sum_s \dot{m}_s ex_s + \dot{E}_d \quad (7)$$

The specific exergy of the system flow, disregarding the kinetic, potential and chemical portions, can be obtained through equation (8):

$$ex = h - h_0 - T_0(s - s_0) \quad (8)$$

It is also important to calculate the analysis of the flow of exergy in each component of the cycle. This calculation takes into account input exergy or input rate ( $\dot{F}$ ), output exergy or product rate ( $\dot{P}$ ) and losses or irreversibility rate ( $\dot{I}$ ). Then, the irreversibility in a control volume is calculated by the difference between the input and the exergetic product as shown in equation (9):

$$\dot{I} = \dot{F} - \dot{P} \quad (9)$$

So, exergetic efficiency, also known as second law efficiency, can be obtained through equation (10):

$$\eta_{ex} = \frac{\dot{P}}{\dot{F}} = 1 - \frac{\dot{I}}{\dot{F}} \quad (10)$$

## 2.5 Economic modelling

For the economic modeling of the Regenerative ORC, the parameters proposed by Moreira and Arrieta (2019) were adopted. However, as an improvement to the work of Moreira and Arrieta (2019) in terms of cost modeling, the cost of working fluid ( $C_{FT}$ ) was included in the cost estimate calculations, which are calculated as follows.

The specific investment cost, which is the relation between the total investment cost and the net power generated by the ORC, can be calculated using equations (11) and (12).

$$I = \frac{I_T}{\dot{W}_c} \quad (11)$$

$$I_T = \sum_i C_{BM,i} + C_C + C_F + C_{SD} + C_{AB} + C_{OS} + C_{FT} \quad (12)$$

Where  $C_{BM,i}$  are the direct and indirect costs related to a component, such as its purchase price, materials for installation, direct labour costs, freight, insurance, taxes, and contractor engineering expenditures. According to Ulrish (2004), the sum of the contingency costs ( $C_C$ ) and fees ( $C_F$ ) is equal to 1.18, and the sum of the costs of auxiliary facilities, consisting of costs for site development ( $C_{SD}$ ), auxiliary buildings ( $C_{AD}$ ) and off-site facilities ( $C_{OS}$ ), is equivalent to 1.30. Finally,  $I_{2010}$  and  $I_{2016}$  are dimensionless index factors for the years 2010 and 2016, respectively.

For the calculation of the  $C_{FT}$ , the geothermal plant of Erdwärme - Grunüwald, in the south of Munich in Germany, was taken into account. The data were obtained in 2010, when it considers 50 tons of isobutane in a 4.3 MWe plant. Equation (13) relates the data obtained in the geothermal plant in 2016:

$$C_{FT} = \left[ \text{€}_{2010} \cdot \frac{I_{2016}}{I_{2010}} \cdot T_{\text{€}/\text{R}_{2016}} \right] \cdot \left( \frac{\text{MWe}}{4.3} \right)^{0.6} \quad (13)$$

Equation (13) considers the scale effect of the plant in terms of power. Where  $\text{€}_{2010}$  is the price of 50 tons of isobutane and is equivalent to 150,000 [€],  $T_{\text{€}/\text{R}_{2016}}$  is the rate conversion from euros to reais [R\$] and MWe is the power produced in the Regenerative ORC [MWe]. To obtain the specific cost for generating electricity through the ORC, in which the portions corresponding to the costs of investment, operation and maintenance of the system are expressed in equation (14).

$$C = I \left( \frac{AF}{HO} \right) + CO\&M \quad (14)$$

Where  $C$  is the Specific Cost for Electricity Production [R\$/kWh],  $AF$  is the Amortization Factor [year-1],  $HO$  is the annual number of operation hours in the cycle [h/year] and  $CO\&M$  is the ORC specific operation and maintenance cost [R\$/kWh]. The amortization factor is shown in equation (15):

$$AF = \frac{j(1+j)^n}{(1+j)^n - 1} \quad (15)$$

Where  $j$  is the interest rate [%] and  $n$  the lifetime [years]. The economic feasibility of using a thermodynamic system of a regenerative ORC in a cement plant was calculated. Therefore, in an energy cogeneration system, the indicators to be evaluated are the net present value (NPV), the internal rate of return (IRR) and the time to return on capital (TR). These indicators will be calculated using equations (16), (17) and (18):

$$NPV = \sum_{n=0}^n \frac{FC_n}{(1+i)^n} \quad (16)$$

$$\sum_{n=0}^n \frac{FC_n}{(1+IRR)^n} = 0 \quad (17)$$

$$TR = \frac{I_T}{FC_n} \quad (18)$$

Even not having constructive information about the project, such as length and diameter of pipes, number and types of accessories in the networks, etc., which could make it possible to estimate the volume of fluid needed and its costs, the value provided by the Erdwärme plant was considered as a reference, as previously mentioned. All costs were calculated in US dollars converted into Brazilian currency at an exchange rate of 3.75 R\$/US\$ referring to the date of 28/02/2019.

## 2.6 Optimization

The optimization of the operational parameters of the investigated cycles was intended to find the maximum value of net power produced by the ORC with the selected organic working fluids. Therefore, the maximization of the net power generated by the ORC was defined as an objective function in the optimization. Regarding the operational parameters, the regenerative ORC was optimized in the operational condition by modifying 8 parameters. The first two varied parameters were pressure and temperature at the turbine inlet. The third and fourth were the pressure ratio between  $P_2$  and  $P_1$  and between  $P_3$  and  $P_1$ . The other varied parameters were the temperature differences between the inlet and outlet of the REG, the difference in sub-cooling temperature in the economizer, the temperatures differences between the entry of the exhaust gases in the evaporator O1 and the outlet of the working fluid in the equipment and, finally, the temperature differences between the fluid inlet in the evaporator O2 and the outlet of the exhaust gases in the equipment.

This logic was adopted in the optimization of net power and other operating parameters. Therefore, all optimizations had different ranges of variation of the operating parameters and restrictions applied to the regenerative ORC for each studied mixture, changing only the objective function depending on the focus of the analysis. The parameters considered during the execution of the optimizations by the conjugate gradient method and the restrictions were applied to the cycle. The conjugate gradient method present in the *EES* library was used to optimize the mentioned variables.

## 3. RESULTS AND DISCUSSION

In this chapter, the results found in the development of this study are presented and discussed. Initially, the results of the modeling of the ideal ORC are evaluated. Soon thereafter, the thermodynamic and economic results obtained in the optimization of the proposed cycle with the maximization of net power as an objective function are shown and compared.

### 3.1 The ideal ORC

Using the references of the zeotropic mixtures and in order to obtain a better composition of these mixtures in the presented regenerative ORC, an Ideal ORC was elaborated, with the input parameters to be worked in the suggested cycle, in order to compare and select the mixtures and compositions with better performances. In order to observe which of the mixtures obtained the best specific net power considering the composition of each studied mixture, Figure 3 shows the comparison of all mixtures according to the input pressure and the calculated specific net power.

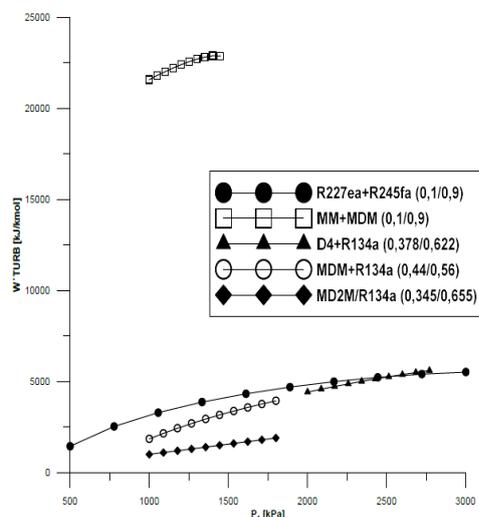


Figure 3. Comparison of all studied mixtures.

It can be observed that MM/MDM mixture presented the best specific net power in the ideal ORC studied, but the condenser outlet pressure was lower than the atmospheric pressure, being 3.727 kPa, therefore it would be necessary to make the vacuum in the condenser, increasing the total cost of the system. Thus, the MM/MDM mixture was discarded from the study. The other mixtures, R227ea/R245fa, MDM/R134a, MD2M/R134a and D4/R134a, even though the specific net power is not very high, were used to compare the performance and total cost of operation in order to find the most suitable mixture, that is, to provide greater specific power, greater thermal and exergetic efficiency and lower specific investment cost to the regenerative ORC.

The most important results found in the simulation of the ideal cycle at the point of maximum production of specific net power and thermal efficiency such as the optimum operating pressure and temperature at the inlet turbine are shown in Table 2. After determining the optimum operating pressure for each working fluid in the ideal ORC, it was used as input during the optimizations of the real regenerative ORC proposed in this study.

Table 2. Results of the simulation of the ideal ORC.

Mixture	$P_1$	$T_1$	Molar fraction	$\eta_{TH}$	$\dot{W}_c$
	[kPa]	[K]	-	[%]	[kJ/kmol]
R227ea/R245fa	3000	411,8	0,100/0,900	16,85	5520
MDM/R134a	1800	506,3	0,440/0,560	5,31	3944
MD2M/R134a	1900	537,8	0,345/0,655	5,21	4465
D4/R134a	2770	538,8	0,378/0,622	6,91	5606

### 3.2 Results for optimized $\dot{W}_c$

After the variations of the parameters in order to obtain the minimum and maximum limits of each one, with the purpose of maximizing the net power produced by them, the new input parameters were modeled and optimized. In this phase, the main thermodynamic results obtained in the optimization in the studied of the regenerative ORC are shown in Table 3.

Table 3. Main optimization results of the regenerative ORC.

Mixture	$\dot{W}_c$	$\eta_{TH}$	$\eta_{ex}$	I
	[kW]	[%]	[%]	[R\$/kWh]
R227ea/R245fa	3295	15,690	34,81	0,1324
MDM/R134a	1054	4,378	9,41	0,2472
MD2M/R134a	1049	5,665	11,67	0,2327
D4/R134a	1615	6,090	3,54	0,1896

The R227ea/R245fa mixture surpassed all other working fluids studied under the prism of produced net power and thermal and exergetic efficiencies. In the comparison of the results demonstrated, it was observed that the ideal ORC, presented in section 3.1, was able to expand the generation of net power for all investigated zeotropic mixtures, and among all mixtures, the R227ea/R245fa fluid also presented greater net power in the ideal ORC. The decrease in the performance of the regenerative system occurred due to the increase in the variation of enthalpy in the turbine, caused by the decrease of the superheated steam temperature at the entrance of this component.

Evaluating the behavior of the studied mixtures, the R227ea/R245fa proved to have greater net power in view of the higher mass flow at the inlet turbine, about 31.9%, 31.8% and 49.0% higher than the MDM/R134a, MD2M/R134a and D4/R134a mixtures, respectively. The difference between the input and output enthalpy of the ORC turbine also generated more net power and increased the thermal and exergetic efficiencies of the system using this mixture. The mass flow rates presented to the other mixtures were lower and even inexpressive. It was also noticed that in the perspective of exergetic efficiency of this mixture, there was a smaller portion of exergy destroyed and that the increase production of net power together with the lesser destruction of exergy in the cycle led to an improvement in the exergetic efficiency of the system. The other mixtures expanded the entropy production in the cycle components, which caused an increase in irreversibility losses and, as a consequence, a decline in the cycle's exergetic performance.

#### 3.2.1 Cost estimation with optimized $\dot{W}_c$

Through the results, it was verified that the configurations for MD2M/R134a and D4/R134a mixtures reached lower total investment costs than the others as shown in Figure 4a. The average decrease in this parameter obtained by the cycle operating with the R227ea/R245fa mixture corresponded to 8.08% and 6.52% for the MDM/R134a mixture in comparison to the other two.

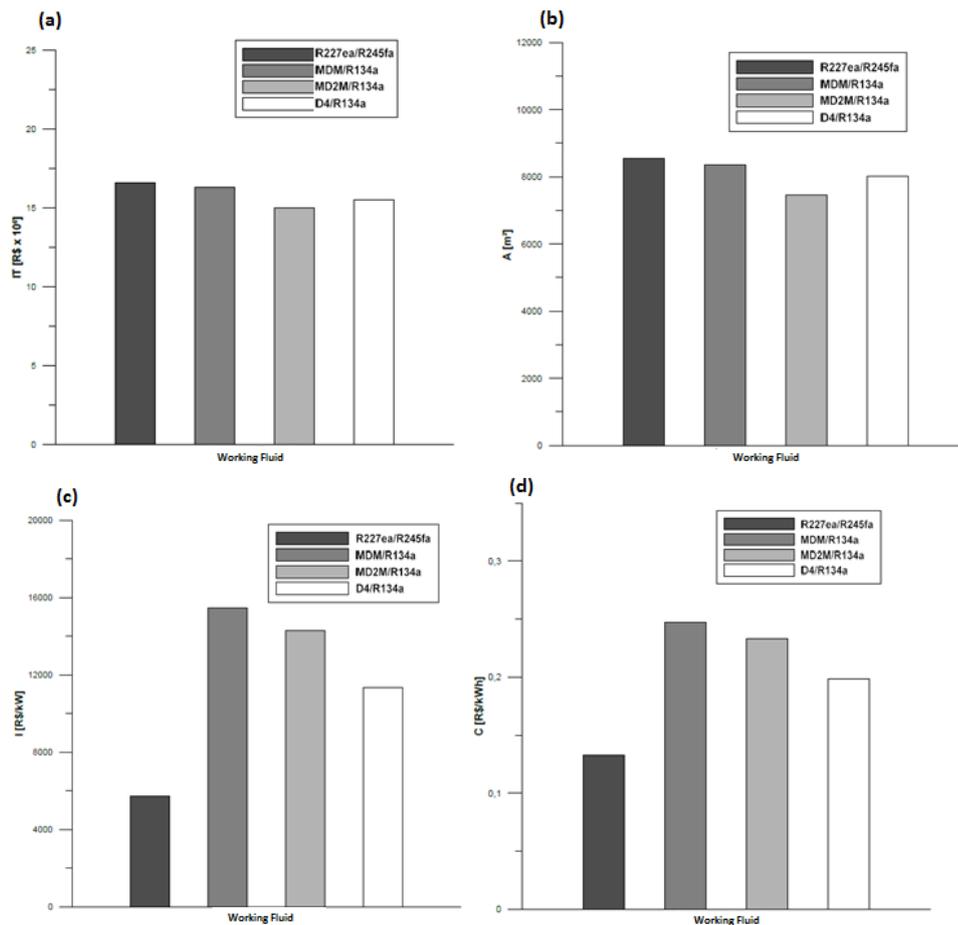


Figure 4. Results of the cost estimating in terms of total capital cost (a), the heat transfer surface area for heat transfer (b), the specific investment cost (c) and the specific electricity generation cost (d).

As a result, the cycle operated using heat exchangers with reduced dimensions and lower costs, which positively influenced the total investment costs of the ORC in general. Figure 4b contrasts the surface heat transfer area of the mixers. Furthermore, it was found that the R227ea/R245fa mixture proved to be more attractive from an economic perspective, since working with this fluid the ORC required less financial support and was able to achieve a higher specific power compared to the other three mixtures investigated in this same conjuncture.

When the object of the investigation was the specific cost of the investment (Figure 4c), the pattern of cost behavior found in Figure 4b has not been maintained, since this indicator is related both to the total investment cost and to the generation of net power. So, as the R227ea/R245fa mixture obtained a higher specific power than all other mixtures, even though the surface area of heat transfer was the largest found, the specific investment cost reached lower levels than the other mixtures.

Comparing the results of the mixtures, there was an average decrease of 9760 R\$/kW (63.04%) in the specific investment cost for the R227ea/R245fa fluid compared to the MDM/R134a. While, compared to the MD2M/R134a fluid, this average decrease was 8585 R\$/kW (3.46%). Also, when compared with the D4/R134a mixture, this proved to be, on average, 5638 R\$/kW (49.63%) more expensive than the R227ea/R245fa mixture.

In the context of the specific cost for electricity generation, the results of this parameter were found to be in line with the other results of the cost estimate. According to the information provided in Figure 4d, the working fluid that exhibited the lowest cost for electricity production among the fluids examined was also R227ea/R245fa. Also, according to Figure 4d, average cost decreases to generate electricity of 46.44%, 43.25% and 33.37% for the mixtures MDM/R134a, MD2M/R134a and D4/R134a, respectively, were shown, in comparison with R227ea/R245fa fluid.

For comparison, while the highest cost calculated up to this point corresponded to 0.2472 R\$/kWh of the ORC operating with the MDM/R134a mixture, the average electricity supply tariff for the industrial class adopted by CEMIG in the year 2018 was 0.4213 R\$/kWh according to the Electric Sector Management Department (DGSE) (DGSE, 2018).

Thus, the estimated cost for generating electricity by recovering residual heat in the cement industry through the ORC in this relatively simple analysis, showed a potential reduction in the price of acquisition of electricity of at least 0.1741

R\$/kWh considering 2018 as a reference. In other words, if the electricity produced by the proposed cycle had been sold in the year in question, there would be a possibility of trading it at 41.32% lower than the value of the electricity tariff practiced by CEMIG for this type of consumer electricity. This significant difference in the cost of generating electricity is justified by the fact that the energy input of the ORC has zero cost, which in this case is the exhaust gases from the cement production process released into the atmosphere.

### 3.2.2 Results of the economic modeling

Based on the results of the cost estimate, the economic indicators were calculated considering the lifetime of 20 years. According to the NPV results for the regenerative ORC operating with all mixtures (Fig. 5), it was found that in addition to the values reaching figures between 20.84 and just over 83 million reais, the mixture that showed the best yield thermodynamic (R227ea/R245fa), was also superior to the other three working fluids with regard to NPV.

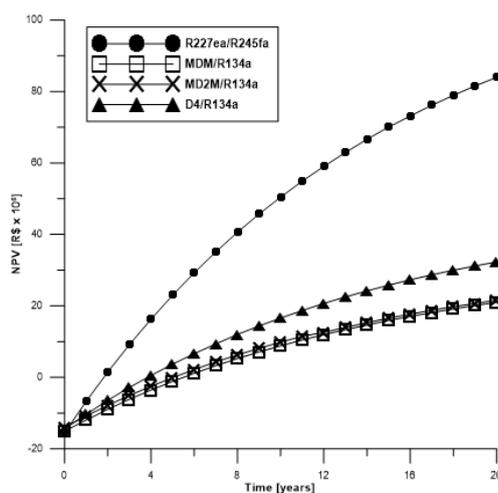


Figure 5. Results of Net Present Value for the regenerative ORC.

The results also showed that the R227ea/R245fa mixture proved to be the most attractive when referring to TR, achieving average reductions in the TR of 37%, 40% and 50% for the mixtures MDM/R134a, MD2M/R134a and D4/R134a, respectively. Finally, in assessing the economic attractiveness through the IRR, it was found that the cycles for energy cogeneration developed in this work proved to be quite interesting economically operating with all the working fluids examined, as the results behaved, without exceptions, significantly above the TJLP. Furthermore, it was found that the MDM/R134a mixture had the highest IRR level with 83.91%.

## 4. CONCLUSIONS

The technical-economic analysis of the regenerative ORC operating with zeotropic mixtures for cogeneration in the cement industry allowed us to conceive the following conclusions:

- When analyzing the behavior of the mixtures in the Ideal ORC, the MM/MDM mixture showed a higher specific power. However, the condenser outlet pressure was lower than the atmospheric pressure, being 3.727 kPa. Therefore, it would be necessary to vacuum the condenser, increasing the total cost of the system. Thus, the MM/MDM mixture was discarded from the study;
- The selected mixtures for the study were R227ea/R245fa, MDM/R134a, MD2M/R134a and D4/R134a, the molar fraction proportions chosen were 0.1/0.9, 0.44/0.56, 0.345/0.655 and 0.378/0.622 respectively.
- The R227ea/R245fa mixture demonstrated superiority when contrasted with the other mixtures from the perspective of generated net power (3295 kW), on average of 31.9% (1054 kW), 31.8% (1049 kW) and 49.0% (1615 kW) when compared with mixtures MDM/R134a, MD2M/R134a and D4/R134a, respectively;
- Average costs declined to generate electricity of 46.44% (0.2472 R\$/kWh), 43.25% (0.2233 R\$/kWh) and 33.37% (0.1987 R\$/kWh) for MDM/R134a, MD2M/R134a and D4/R134a mixtures, respectively compared to fluid R227ea/R245fa (R\$ 0.1324/kWh);
- Based on the results of the cost estimate, if the electricity generated by the proposed ORC had been sold in 2018, there would be the possibility of trading it at a value 41.32% lower than the value of the electricity tariff practiced by CEMIG for the industrial-class consumer of that year;

- The NPV values calculated for all mixtures studied were between 20.84 and just over 83 million reais. The mixture that exhibited the best thermodynamic performance (R227ea/R245fa), was also superior to the other three working fluids with regard to NPV;
- The lowest TR value obtained in this study (2.65 years) was displayed by the regenerative ORC operating with the R227ea/R245fa mixture;
- All the configurations analyzed proved to be interesting from the perspective of IRR, since they showed values above the TJLP adopted in this work. In addition, the MDM/R134a mixture reached the highest IRR level in this study (83.91%);

## 5. ACKNOWLEDGEMENTS

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