

## COGENERATION IN CEMENT INDUSTRY WITH SIMPLE ORC

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**Abstract.** *This work aims to estimate the specific investment and the generation cost for the use of an Organic Rankine Cycle to the recovery of waste heat in the cement industry. Working fluids were selected from some requirements, such as safety, environmental impacts and entropic behavior in the expansion process carried out in the turbine. Then the optimal operating pressure was calculated and the effect of overheating assessed in order to find the optimal operating temperature at the turbine inlet. Finally, by using the Engineering Equation Solver (EES), the maximum thermal efficiency for each fluid in the cycle studied was calculated. The values of maximum efficiency for the refrigerants that showed better results, R141b and R123, were respectively 23.14% and 21.24%. From these fluids, there was the R141b which had the lowest power generation costs (0.2786 R\$/kW.h) and specific investment costs (5,376 R\$/kW), for an estimated installation cost of R\$ 8,449,000.00. In the region of Minas Gerais, we concluded that the R141b is the best working fluid to be used in Organic Rankine Cycle to waste heat recovery in the cement industry.*

**Keywords:** *Organic Rankine Cycle, thermal efficiency, cement industry.*

### 1. INTRODUCTION

In Brazil millions of tons of cement are produced per year. The cement industry is one of the main sectors that influences the Brazilian's economic development. Today the country is going through a period characterized by the scarcity of energy resources, which contribute to the creation of a culture of sustainability.

The cement industry sector represents 2.0% of the final energy consumption in the Brazilian' industrial sector. The cement industry uses more intensively petroleum coke (70.5%) and electricity (12.8%), both represents ~ 0.075 tep/t of clink. The electricity consumption is around 0,112 MWh/t of clink, (BEN, 2015).

In the cement manufacturing process, usually the waste heat that from the burning of clink (raw material of cement) is discharge on the atmosphere. To use the energy cogeneration in the waste heat recovery, thermodynamic cycles such as the Organic Rankine Cycle (ORC) are used. This cycle is a Rankine cycle and an organic fluid used in place of water as working fluid. The ORC consists of a boiler, which transfers heat to the working fluid, a turbine that produces work by expanding fluid and a condenser that leaves the fluid in the ideal condition to be pumped back into the boiler, starting the cycle again. The heat from the exhaust gases of the clink's burning in the cement industry is used as the external heat source for the boiler in this ORC.

### 2. LITERATURE REVIEW

Hillel Legmann (2001) studied the use of residual heat in the cement industry with steam boilers. The heat recovery system operates in the Organic Rankine Cycle (ORC). The own energy generation process (preheating, vaporizing, expansion, pumping, and condensing the organic working fluid) takes place at OEC unit (Energy Converter Ormat), operating in an automatic mode. They are recovered on average 8.2 MW for a total of 20.2 MW of waste heat that would otherwise be wasted.

Hung (2001) investigated the operation efficiency of organic fluids operating in the Organic Rankine Cycle (ORC). It was attested that the operation of this cycle is directly dependent on two factors: the cycle conditions and the thermodynamic properties of the working fluids. In the study, the R113 and R123 fluids obtained a better performance at low temperature in the waste heat recovery. Pedro J. Mago and others (2007) made a comparison of simple ORC with regenerative ORC incorporating this analysis of dry organic fluids. It was concluded that the R113 is the fluid that showed the best thermal efficiency according to its boiling temperature at the turbine inlet at  $T = 47.59^{\circ}\text{C}$  and the isobutane presented the worst thermal efficiency. They analyzed the most used and best performing fluids. They concluded that R134a, R245fa, n-pentane and silicone oil showed good temperature range in terms of efficiency. AnhLai Ngoc et al. (2011) investigated the potential of pure working fluid to high temperature ORC. It was observed that cyclopentane was the best working fluid with respect to other fluids presenting exergetic efficiency equal to 38%, while the second best was the o-xylene with 37% of exergetic efficiency. Quoilin Sylvain et al. (2011) compared different working fluids (R245fa, R123, n-butane, n-pentane, R1234yf and Solkatherm) for waste heat recovery, in an Organic Rankine Cycle proposed by them. The n-butane has the best thermodynamic and economic optimization.

Vélez et al. (2012) presented a brief summary of several studies that discuss the viability and cost of using the Organic Rankine Cycle (ORC) for cogeneration. It was concluded that the ORC is an important energy cogeneration technology demonstrating considerable efficiency for residential and/or industrial facilities. Rettig et al. (2011) presented a project in which the process of Cement industry has on average 34% loss of heat. This heat recycling would result in an increase of 70% to 80% thermal efficiency of the furnace by making use of interesting and viable ORC. Wang et al. (2009) showed the Exergy analysis and parameter optimizations for different cogeneration power plants in the cement industry. The Organic Rankine Cycle was less efficient due to its low grade waste heat recovery and Kalina cycle had better performance for use in the cement industry.

### 3. METHODOLOGY

The grinding of raw materials for cement production produces a fine powder known as raw powder, which is preheated and then introduced into a rotary kiln. The material is heated to a temperature of approximately 1.500°C before being suddenly cooled by blasts of air. Clinker, the basic material required for the production of all types of cement, is thus produced. According to Sharma (2013), for a cement factory clink capacity of 5000 t/day, the furnace releases exhaust gases with a mass flow of 89.54 kg/s at a temperature of approximately 350°C in the atmosphere. The gas composition in molar base is: 26.3% of CO<sub>2</sub>; 64.58% of N<sub>2</sub>; 4.94% of O<sub>2</sub>; 4.18% of H<sub>2</sub>O. By directing such gases to the boiler ORC, it is possible to reuse the heat of the gases carrying out a heat exchange with the working fluid.

First working fluids were selected from some requirements, such as safety, environmental impacts and entropic behavior. Second the optimal operating pressure in the boiler was calculated in order to maximize the work of the expansion process carried out in the turbine considering the exhaust steam around 35°C. Then the pressure was varied in the heater seeking maximum thermal efficiency. Analyzing the results, five fluids were selected (R123; R141b; R245fa; R600 and R600a) and the superheating steam at the turbine inlet was performed to increase the thermal efficiency. Defining the final system configuration (Fig. 1) the maximum power, the investment cost and the cost of power generation were calculated. The above calculations were performed using the software Engineering Equation Solver (EES).

#### 3.1 System description

The considered ORC with direct contact heater is shown in Fig. 1. The cycle consists of a two-stage turbine, one water cooler condenser, two pumps, an economizer, an evaporator, and a superheater. The working fluid follows the direction indicated by the arrows operating as follows: first the fluid is heated to a superheated vapor state in the boiler superheater and is expanded through the turbine, where a fraction of the mass flow of fluid is drawn into the deaerator (first stage), after passing through the second turbine stage the steam will produce shaft work. It is then transformed in saturated liquid while passing through the condenser. Then it is pumped to the heater and mixed with the fraction extracted from the first turbine stage, and finally pumped back into the superheater through the economizer and the evaporator.

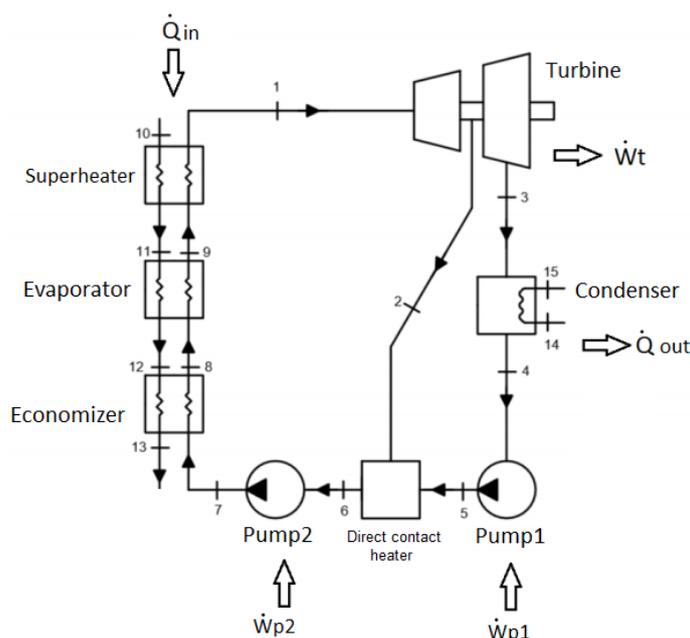


Figure 1. Organic Rankine Cycle with direct contact heater

### 3.2 Thermodynamic Analysis

Thermodynamic analysis has been proposed to analyze ORC configurations based on energy balance as follows. The calculation in EES is initiated by computing the fluid specific enthalpy ( $h$  in kJ/kg) and mass flow ( $m$  in kg/s). The next step is to apply the energy balance to each component.

Pump work ( $\dot{W}_p$  in kW) - Eq. (1):

$$\dot{W}_p = \dot{m} \cdot (h_3 - h_4) \quad (1)$$

Heat input ( $\dot{Q}_{HE}$  in kJ/s) - Eq. (2):

$$\dot{Q}_{HE} = \dot{m} \cdot (h_1 - h_4) \quad (2)$$

Turbine work ( $\dot{W}_T$  in kW) - Eq. (3):

$$\dot{W}_T = \dot{m} \cdot (h_1 - h_2) \quad (3)$$

Heat output ( $\dot{Q}_C$  in kJ/s) - Eq. (4):

$$\dot{Q}_C = \dot{m} \cdot (h_3 - h_2) \quad (4)$$

The specific net power is defined as follows in Eq. (5):

$$\frac{\dot{W}_{net}}{\dot{m}} = \frac{\dot{W}_T - \dot{W}_p}{\dot{m}} \quad (5)$$

The thermal efficiency ( $\eta_{th}$ ) is defined as follows in Eq. (6):

$$\eta_{th} = \frac{\dot{W}_{net}}{\dot{Q}_{HE}} \quad (6)$$

In the equations 1 to 6, the  $h$  is the specific enthalpy, in kJ / kg.K;  $\dot{m}$  the is the mass flow rate, in kg / s;  $\dot{Q}_{HE}$  is the heat input, in kW;  $\dot{Q}_C$  is the heat output, in kW;  $\dot{W}_T$  is generated in the power turbine, in kW;  $\dot{W}_p$  is the power consumed by the pump, in kW,  $\dot{W}_{net}$  is the net power of the Rankine cycle, in kW; and  $\eta_{th}$  it is the net thermal efficiency of the cycle.

### 3.3 Estimated cost of electricity generated

According to Junior et al. (2015), it is necessary to calculate the area that performs heat transfer in heat exchangers, to obtain their costs. For the development of the calculation we used the method of differences of logarithmic average temperatures (Incropera, 2007), expressed in Eq. 7.

$$q = \bar{U} \cdot A \cdot \Delta T_m = \bar{U} \cdot A \cdot \left[ \frac{(T_{h,out} - T_{c,in}) - (T_{h,in} - T_{c,out})}{\ln[(T_{h,out} - T_{c,in}) / (T_{h,in} - T_{c,out})]} \right] \quad (7)$$

Where in the last equation the  $q$  is the heat transfer rate, in W;  $\bar{U}$  is the overall heat transfer coefficient, in W/m<sup>2</sup>.K;  $A$  is the area, in m<sup>2</sup>;  $\Delta T_m$  is the logarithmic mean temperature difference, in K;  $T_{h,out}$  is the system fluid temperature exiting, in K;  $T_{h,in}$  system fluid temperature entering, in K;  $T_{C,int}$  is the system fluid temperature exiting, in K;  $T_{C,in}$  is the cooling fluid entering temperature, in K. For the superheater, evaporator and economizer  $U = 7$  W/m<sup>2</sup>.K and for the condenser  $U = 125$  W/m<sup>2</sup>.K. For all of the equipments  $A = 5,6745$  m<sup>2</sup> and  $\Delta T_m = 0.001$  K.

The overall heat transfer coefficient ( $U$ ) is determined by the average value ranges defined by Walas (1990) for various types of processes that occur during the cycle.

With the values of the areas of heat exchangers and other cycle parameters (pump volumetric flow, deaerator volume for one hour of operation and turbine generated power) were calculated the costs of the major equipment ( $CE$ ) by interpolation cost curves given, in 1998 US\$, by Loh (2002). The results of the aforementioned parameters were converted by multiplying the correction factor ( $CF$ ) of the year 2013 of the costs industrial equipment supplied by Bridges (2014). The *Dolar* is the exchange rate at December of 2013 that was used to convert the result to local currency (Equation 8), considered in 2.34 R\$/US\$ (Banco Central do Brasil).

$$CE_{2013} = CE_{1998} \cdot CF_{1998-2013} \cdot Dolar \quad (8)$$

Given the relationship of the equation 9, suggested by Bejan and others (1996), it determined the total cost of the installed system ( $CTI$ ), being  $CTE$  the total cost of equipment referenced for December 2013, in R\$. The constant 4,16 constant was suggested by Bejan and others (1996), which includes the costs to the system installation.

$$CTI = 4,16 \cdot CTE \quad (9)$$

Equation 10 expresses the amortization factor ( $AF$ ), in year<sup>-1</sup>, considering life time ( $n$ ) in 20 years, and long-term interest rate ( $i$ ), considered by 6% year.

$$AF = \frac{i \cdot (1+i)^n}{(1+i)^n - 1} \quad (10)$$

For the calculation of Generation Cost  $C_{ger}$  (in R\$/MWh), expressed in equation 11 was adopted (base on average annual costs) an operation and maintenance cost ( $CO\&M$ ) of the 0.225 R\$/kWh and the hours of annual operation ( $HO$ ) in 8030 h / year.

$$C_{ger} = \frac{CTI \cdot FA}{HO} + C_{O\&M} \quad (11)$$

#### 4. RESULTS AND DISCUSSION

Table 1 shows the results for turbine inlet temperature, boiler pressure, direct contact heater operating pressure, and thermal efficiency at maximum specific work condition for the different fluids after thermodynamic optimization. It is observed that the refrigerant R141b has the best result for the thermal efficiency (0.23142), and also had the lowest operating pressure in the direct contact heater (815.3 kPa). On the other hand, the specific work is higher for R600 yielding (132.2 kJ/kg).

Table 1. Thermodynamic results at maximum specific power condition.

Fluid	T (K)	$P_{boiler}$ (kPa)	$P_{boiler}$ (kPa)	$\eta_{th}$	$\frac{\dot{W}_{max}}{\dot{m}}$ (kJ/kg)
R123	448.63	2801.57	825.0	0.21241	75.97
R141b	483.76	2999.00	815.3	0.23142	119.70
R245fa	421.36	2816.59	971.9	0.17772	71.44
R600	416.92	2977.92	1193.0	0.17494	132.20
R600a	401.36	2865.86	1317.0	0.15404	105.60

Table 2 shows the heat rate input values in the cycle, pump's power, turbine power and net power output of the cycle at the same condition of Tab. 1. These values represent the amount of energy that can be produced (reuse) using the existing energy in the exhaust gas that was considered. According to these results, R141b fluid income less cycle heat input (6798 kW) and pump's work (68 kW), and has the highest turbine power output (1640 kW) and, consequently, also the higher net cycle power (1572 kW) than the other fluids analyzed.

Table 2. Thermodynamic cycle results

Fluid	$\dot{Q}_{HE}$ (kW)	$\dot{W}_P$ (kW)	$\dot{W}_T$ (kW)	$\dot{W}_{net}$ (kW)
R123	6956	79	1555	1476
R141b	6798	68	1640	1572
R245fa	6856	75	1292	1217
R600	6969	96	1313	1217
R600a	6887	98	1157	1059

Table 3 shows the installation costs, the specific installation cost and the generation cost at the same maximum specific work condition. It is observed that the fluid R600a has the lowest installation cost (R\$ 8,246,000.00), however, has the highest specific installation cost (7,786.00 R\$/kW) and generation cost (0.3027 R\$/kW.h) caused by the lower generated power. The R141b fluid had the lowest values for generation cost (0.2786 R\$/kW.h) and specific installation cost (5,376 R\$/kW), also ranked in second place in relation to the installation cost R\$ 8,449,000.00.

Table 3. Installation cost, specific installation cost and generation cost.

Fluid	Installation cost (R\$)	Specific installation cost (R\$/kW)	Generation cost (R\$/kW.h)
R123	8564000	5802	0.2829
R141b	8449000	5376	0.2786
R245fa	8507000	6992	0.2948
R600	8655000	7109	0.2959
R600a	8246000	7786	0.3027

The final cycle of the fluid that has better thermodynamic and economic optimization was the R141b cycle. Below we have the Txs diagram and the table of values for the states of this fluid in its cycle.

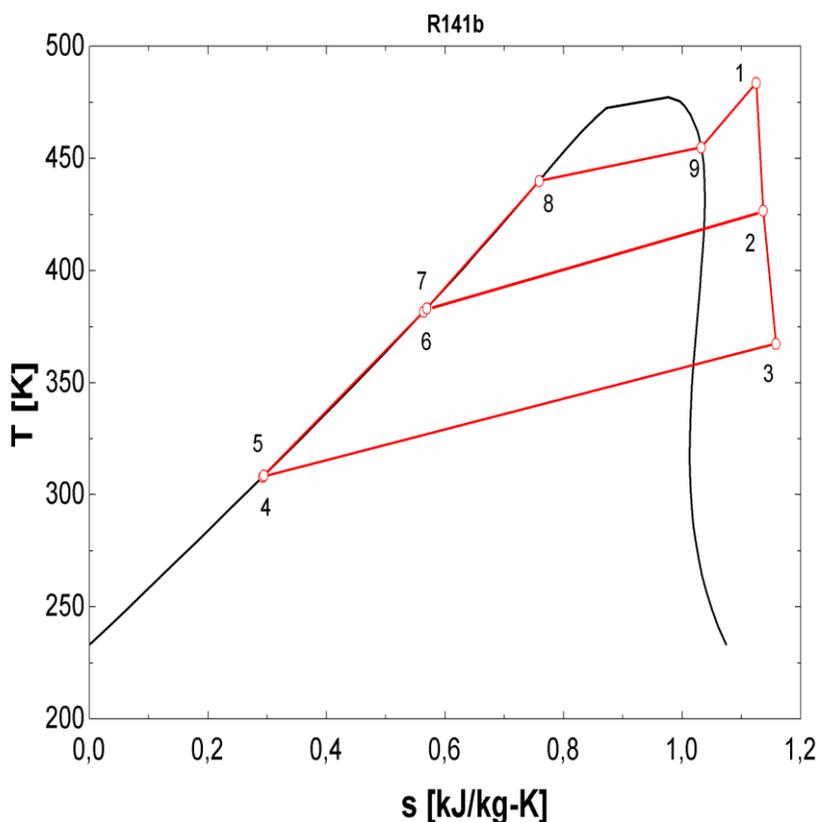


Figure 2. Temperature entropy diagram of the refrigerant R141b.

Table 4. Thermodynamic results for R141b.

State	m (kg/s)	P (kPa)	T (K)	h (kJ/kg)	s (kJ/kg.K)	V (m <sup>3</sup> /kg)	ρ (kg/m <sup>3</sup> )	x (-)
1	27.42	2999.00	483.76	423.16	1.1249	0.0082	122.5	n.a.
2	8.143	815.30	426.71	394.46	1.1369	0.0332	30.1	n.a.
3	19.28	112.21	367.34	350.23	1.1584	0.2275	4.4	n.a.
4	19.28	112.21	308.15	79.13	0.2924	0.0008	1215.0	0
5	19.28	815.30	308.64	79.71	0.2942	0.0008	1214.0	n.a.
6	27.42	815.30	381.71	173.17	0.5636	0.0010	1050.9	0
7	27.42	2999.00	383.24	175.25	0.5690	0.0010	1047.0	n.a.
8	27.42	2999.00	440.04	255.51	0.7585	0.0011	875.8	n.a.
9	27.42	2999.00	455.04	379.76	1.0323	0.0061	163.5	1
10	89.54	101.32	573.15	-3265.30	7.1009	1.4698	0.7	n.a.
11	89.54	101.32	560.89	-3278.60	7.0774	1.4384	0.7	n.a.
12	89.54	101.32	525.54	-3316.64	7.0073	1.3477	0.7	n.a.
13	89.54	101.32	502.47	-3341.22	6.9595	1.2885	0.8	n.a.
14	156.2	250.00	295.00	91.81	0.3225	0.0010	997.9	0
15	156.2	250.00	303.00	125.27	0.4344	0.0010	995.8	0

## 5. CONCLUSIONS

Based on the results, it is possible to conclude that the R141b working fluid is the preferred fluid for application of an Organic Rankine Cycle for the recovery of waste heat in the cement industry. This fluid showed the best results for a thermodynamic optimization, namely: higher thermal efficiency of 23.14%; lower operating pressure in the heater of 815.3 kPa; higher net cycle power 1,572 kW. Moreover, it also showed the best results for an economic optimization, namely: lower generation cost 0.2786 R\$/kW.h and lower installation cost 5,376 R\$/kW.

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