



COBEM
2021 Florianópolis - Brasil



26th ABCM International Congress of Mechanical Engineering
November 22-26, 2021. Florianópolis, SC, Brazil

COBEM2021-0356

ASSESSMENT OF A RANKINE CYCLE FOR COGENERATION IN CEMENT INDUSTRIES

Nathália de Assis Gomes

Pontifical Catholic University of Minas Gerais, Department of Mechanical Engineering, Av. Dom José Gaspar, 500
CEP 30535-901 – Belo Horizonte – MG – Brazil.
nathaliaassisgomes@gmail.com

Leandro Caetano de Jesus

Pontifical Catholic University of Minas Gerais - Contagem, Department of Mechanical Engineering, St. Rio Comprido, 4.580
CEP 32010-025 – Contagem – MG – Brazil.
leandro.caetano86@hotmail.com

Leonardo de Souza Pinto Pereira

Pontifical Catholic University of Minas Gerais - Contagem, Department of Mechanical Engineering, St. Rio Comprido, 4.580
CEP 32010-025 – Contagem – MG – Brazil.
leolog02@gmail.com

Paulo Victor da Silva Gandra

Pontifical Catholic University of Minas Gerais - Contagem, Department of Mechanical Engineering, St. Rio Comprido, 4.580
CEP 32010-025 – Contagem – MG – Brazil.
paulopv34@hotmail.com

Felipe Raul Ponce Arrieta

Pontifical Catholic University of Minas Gerais, Department of Mechanical Engineering, Av. Dom José Gaspar, 500
CEP 30535-901 – Belo Horizonte – MG – Brazil.
felipe.ponce@pucminas.br

Abstract *The aim of this paper is to analyze, thermodynamically and economically, the application of a conventional Rankine cycle for Waste Heat Recovery (WHR) and power generation in cement industries. The cement production is a process that consumes and wastes a lot of energy, about of 40 % of the total energy consumed for the cement plants is lost in the form of heat. Therefore, in order to improve the performance of this type of factory, the development and application of WHR technologies becomes necessary and important. The worst sources of waste heat in the cement industries are the cyclone pre-heater and the clinker cooler, as these equipment are the responsible for the system main loss, they were chosen as object of this study. The theoretical and actual Rankine cycles were modeled with the General Electric GateCycle™ program (Version 6.0). The data used in the cycles developing were taken from the Apodi cement manufacturing plant, which already contains a WHR system installed. The actual cycle modeled produces 6.29 MW, considered an optimum setting of the system, which corresponds to 21 % from the total electric energy demand of the Apodi plant. An economic study was made, and it showed that, for an investment around R\$57.7 million, the payback time is 3.3 years after the commissioning of the cogeneration plant.*

Keywords: *Cogeneration, Waste Heat Recovery, Rankine Cycle, Power Generation, Cement Industry*

1. INTRODUCTION

The cement industries are huge energy consumers, they consume approximately 2 % of the world's energy. According to Ghalandari et al. (2019), the cement factories require between 90 and 150 kWh of energy, to produce one ton of cement. In addition to this significant energy consumption, cement plants also waste a large amount of thermal energy. Nami and Anvari-moghaddam (2020) identified that 40 % of input energy in cement industries is lost in the form of heat. For these reasons, these industries have high potential for heat recovery and electricity generation. Among the thermodynamic cycles most used for cogeneration, the Rankine cycle is the simplest, cheapest and most efficient. Therefore, it is an attractive and recommended alternative for cogeneration in the cement sector. This cycle implementation is able to decrease the electric demand of the plant by up to 30 %. This also contributes considerably to the company's expenses reduction (Han et al., 2018).

2. LITERATURE REVIEW

There are many studies about of the Waste Heat Recovery in cement industries. According to Madlool et al. (2011), the main heat losses in the cement production process are the exhaust gas from the rotary kiln (315 °C) and the exit hot air from the clinker cooler (215 °C). Atmaca and Yumrutaş (2014) attested to 85.12 % of the total energy consumed by the cement plants is lost mainly through the kiln and the cyclone pre-heaters. This loss corresponds to 71.87 MW, of which 49.08 MW represents the energy loss from the rotary kiln alone. Amarasinghe et al. (2018) also discovered that the waste heat available, in the cement kiln exhaust gas, depends on the raw meal type that is produced in the process: standard or high strength. The Rankine cycle is an option of thermodynamic cycle used for Waste Heat Recovery. Engin and Ari (2005) analyzed the application of a Rankine cycle and a Waste Heat Recovery Boiler in a cement plant. They have found that the suggested system was able to generate 1 MW of power and save 540,000 USD/year. Zeeshan and Arbab (2015) proposed the installation of a Waste Heat Recovery Power Plant (WHRPP) composed of two boilers: one of them responsible for the recovering of the exhaustion gas from cyclone pre-heaters (SP Boiler) and the other for the recovering of the hot air discharged from the clinker cooler (AQC Boiler). The authors pointed that WHRPP is capable of producing 30 million kWh/year of electric energy, which is equivalent to an energy saving of 32.98 %. Irungu et al. (2017) also confirmed that two boilers (SP and AQC) can generate enough energy to supply 33 % of the total factory demand. For their project, it was required a capital investment of 8 million dollars with a payback period of 2.69 years. Tan et al. (2014) designed a two-pressure Rankine cycle for cogeneration in a cement industry. The authors calculated the project ability to produce electricity (6.64 MW), they estimated its initial investment (\$9.7 millions) and its payback time (5.5 years). Mohammadia et al. (2018) compared the two pressure Rankine and Organic Rankine (ORC) cycles. The two pressure Rankine cycle presented a higher power (5.675 MW) and exergetic efficiency (48.03 %) than the two pressure ORC, this happened because of its low turbine outlet temperature. Sanaye et al. (2020) noted that conventional Rankine cycle produces less CO₂, has a shorter payback time, saves more fuel and money than the CRO. Amiri and Vaseghi (2015) also compared the conventional Rankine cycle with the Kalina and supercritical CO₂ cycles. They realized that the conventional Rankine cycle was the most thermally efficient for high temperatures and it had one of the lowest costs. Wang et al. (2009) identified the main responsible for the cycles exergetic losses are, respectively, the turbines (9.3 %), condensers (7.9 %), SP boilers (5.1 %) and AQC boilers (4.5 %). Rad and Mohammadi (2018) optimized a conventional Rankine cycle, changing the inlet maximum pressure of its first turbine. By increasing its value, the cycle efficiency also improved.

3. METHODOLOGY

In this study, two Rankine cycles, theoretical and actual, were modelled with the General Electric GateCycle™ program. According to General Electric (GE), this software can be used to construct thermal power plants and model their design and off-design performances. The input data of the cycle's components were acquired from an Apodi cement plant, located in the city of Fortaleza-Brazil. This plant already has a cogeneration system. However, in this paper, its actual cycle was modeled and optimized in order to improve the system and obtain a higher power production.

3.1 Thermal schematic definition

The theoretical Rankine cycle is composed of two Flash steam tanks, two boilers, a turbine, a condenser and a pump. One of the boilers is responsible for the recovering of the exhaustion gas from the Suspension Preheaters (SP Boiler) and the other one for the recovering of the exit hot air from the clinker cooler (AQC Boiler). The application of the Flash steam tanks is important for supplying extra steam to the turbine and mixing it with the boilers steam. The Figure 1 shows the Rankine cycle schematic. The explanation about the cycle operation is below.

The Rankine cycle starts when cold water is pumped from pump 3 to the AQC boiler economizer. Inside this economizer, the first thermal exchange happens between the cold feed water and the exhaustion hot gases. After this step, part of the economizer's output water is directed to the AQC boiler evaporator, part to the SP boiler evaporator and part to the Flash steam tank 1.

The AQC boiler evaporator transforms the input liquid water in saturated steam. This steam enters in the super heater 1, where it receives heat and it is converted in superheated steam, with enough enthalpy to activate the turbine.

The SP boiler evaporator works likewise the AQC boiler evaporator. It also promotes the phase change of liquid water to saturated steam. The produced steam is superheated in the super heater 2, after this it is mixed with the superheated steam from the AQC boiler and finally, both are directed to the turbine.

The water conducted to the Flash steam tank 1 flows through the valve 1, responsible for reduce its pressure and generate a mixture of steam and saturated liquid. The tank 1 sends the steam of the mixture to the turbine and the saturated liquid to other tank (Flash steam tank 2). In the middle of the way to the tank 2, the work fluid pass through the valve 2, producing again the mixture of steam and saturated liquid. Then, the tank 2 directs the steam to the turbine and the saturated liquid to the pump 3.

In the turbine, the superheated steam is expanded producing work that is able to activate a generator. After the superheated steam expansion, a mixture of steam and liquid is conducted to the condenser. The condenser transforms the steam into liquid and sends it to the pump 2. To condense the steam is used a low temperature water from a cooling water.

The cycle restarts, after the work fluids from the pump 2 and the Flash steam tank 2 are mixed and pumped from pump 3 to AQC boiler.

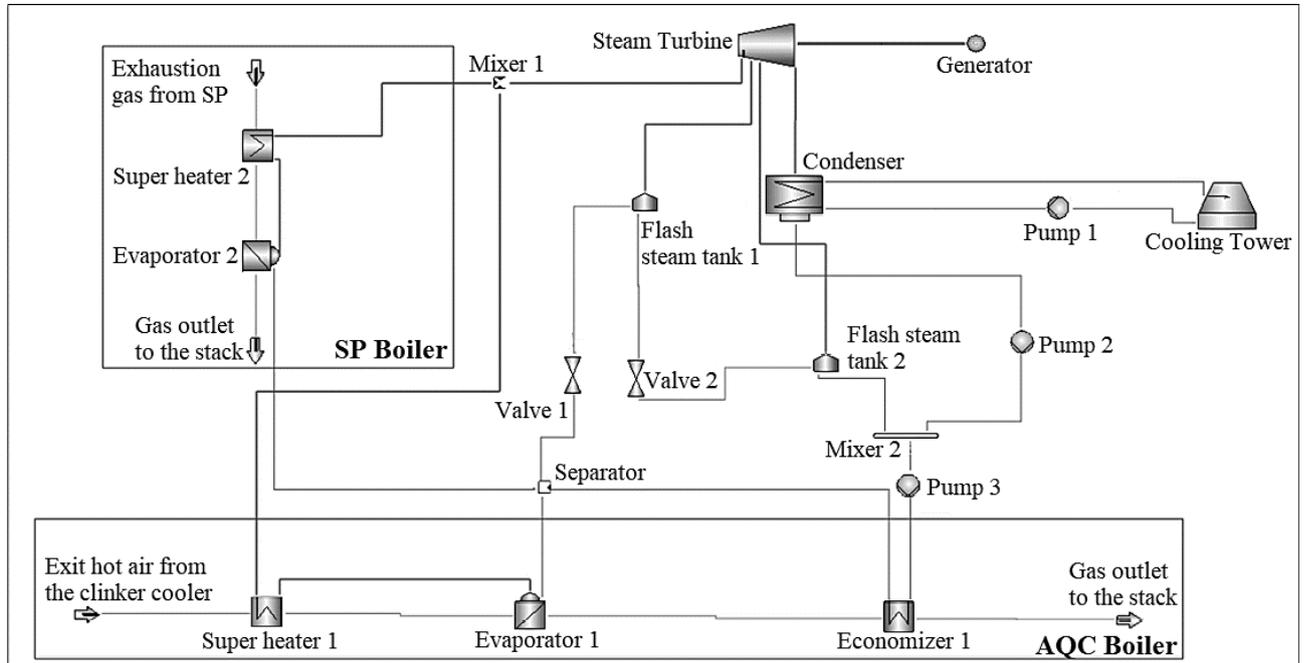


Figure 1. Schematic diagram of the Rankine cycle.

3.2 Input data

To perform the simulation in Gate CycleTM, input operational values were assumed based on data from the WHR system of an Apodi cement plant. In this plant, the output temperature of the clinker cooler is higher than found in most literature. However, this value is consistent with Ghalandari, Majd, and Golestanian (2019). The SP boiler uses the exhaustion gas from the Suspension Preheaters to generate steam. The AQC boiler uses the exit hot air from the clinker cooler to generate steam. Table 1 shows the process data for both boilers. Table 2 contains the configuration of the SP and AQC heat exchangers. Table 3 presents the configurations of the other Rankine Cycle components.

Table 1. Gas input in SP and AQC boilers.

Boiler	Mass Flow Rate, kg/s	Gas Temperature, °C	Gas compositions, %	
SP	88.0	310.0	CO ₂ / N ₂ / O ₂ / H ₂ O	26.30/64.58/4.94/4.18
AQC	48.1	440.0	N ₂ / O ₂	79.00/21.00

Table 2. Heat exchanger's configurations.

Heat exchanger	Parameters	Values
Evaporator 1 – AQC	Temperature difference between cold and hot sources, °C	11
	Global coefficient of heat transfer, kW/m ² K	0.0454
	Energy loss fraction	0.113
Evaporator 2 – SP	Temperature difference between cold and hot sources, °C	30
	Global coefficient of heat transfer, kW/m ² K	0.0454
	Feed water pressure, kPa	0.00
	Desired water purge fraction	0.00
	Energy loss fraction	0.00

Super heater 1 – AQC	Steam output temperature, °C	375
	Global coefficient of heat transfer, kW/m ² K	0.0454
	Passes number of the Heat Transfer Exchange	10
	Maximum steam temperature, °C	593.48
Super heater 2 – SP	Desire efficiency, %	90
	Global coefficient of heat transfer, kW/m ² K	0.0454
	Passes number of the Heat Transfer Exchange	10
Economizer 1 – AQC	Desired sub cooling output, °C	30
	Global coefficient of heat transfer, kW/m ² K	0.0454
	Passes number of the Heat Transfer Exchange	10
	Energy loss fraction	0.01

Table 3. Configurations of Rankine Cycle components

Equipment	Parameters	Values
Pumps 1, 2 and 3	Isentropic efficiency, %	85
	Mass flow rate, kg/s	115.289
	Height, m	1066.813
	Rotation speed, rpm	3600
Turbine	Rotation speed, rpm	3600
	Efficiency, %	85
	Admission pressure 1, kPa	574.0006
	Admission pressure 2, kPa	150.002
	Pressure drop fraction	0.02
	Output pressure, kPa	10
Generator	Maximum input temperature, °C	565.56
	Rotation speed, rpm	3600
	Power, kVA	50,000
	Cooling liquid pressure, kPa	515.04
	Global efficiency, %	98.5
Cooling water	Power factor, %	85
	Fans number	3
	Water pressure, kPa	103.42
Condenser	Maximum water temperature, °C	22
	Output pressure, kPa	10
	Cold water temperature, °C	11.11
	Global coefficient of heat transfer, kW/m ² K	2.85
	Passes number	2
	Minimum allowed pressure, kPa	1.7237
Maximum allowed pressure, kPa	172.37	

3.3 Actual cycle modelling

The actual cycle modelled in GateCycle is also based on the conventional Rankine Cycle. However, it also contains a deaerator, a desuperheater and it does not have a Flash tank. The Figure 2 shows the actual Rankine cycle schematic.

After the modelling of the actual cycle, the cycle components and the total installation costs were calculated. The reference tables from Loh (2002) were used to estimate the equipment cost and they were applied in the Gate CycleTM software. A cost comparison was performed by modifying the components configuration, to increase the plant's power generation.

3.4 Optimization

In this optimization study, the goal was to obtain the maximum net power at the lowest generation cost. The main equipment that was optimized to achieve this goal were the super heaters, the evaporators, the economizer, and the condenser, in other words, the system's heat exchangers. The parameters that were considered for the optimization of the super heaters, condenser, evaporator, and economizer were the steam output temperature, output pressure, Pinch Point and water outlet temperature, respectively. Each parameter selected for optimization presents the range values shown in Table 4. These values were selected based on previous results presented by Varma e Srinivas (2017). In addition, preliminary simulations were performed that allowed these parameters to be adopted in the ranges shown in table 4.

Table 4. Independent parameters for optimization.

Heat exchanger	Parameters	Range
Super heater 1	Output temperature, °C	422 – 436
Super heater 2	Output temperature, °C	280 – 296
Condenser	Output pressure, kPa	10.6 – 14.6
Evaporator 2	Pinch Point, °C	6 – 12
Economizer 2	Water output temperature, °C	174 – 181

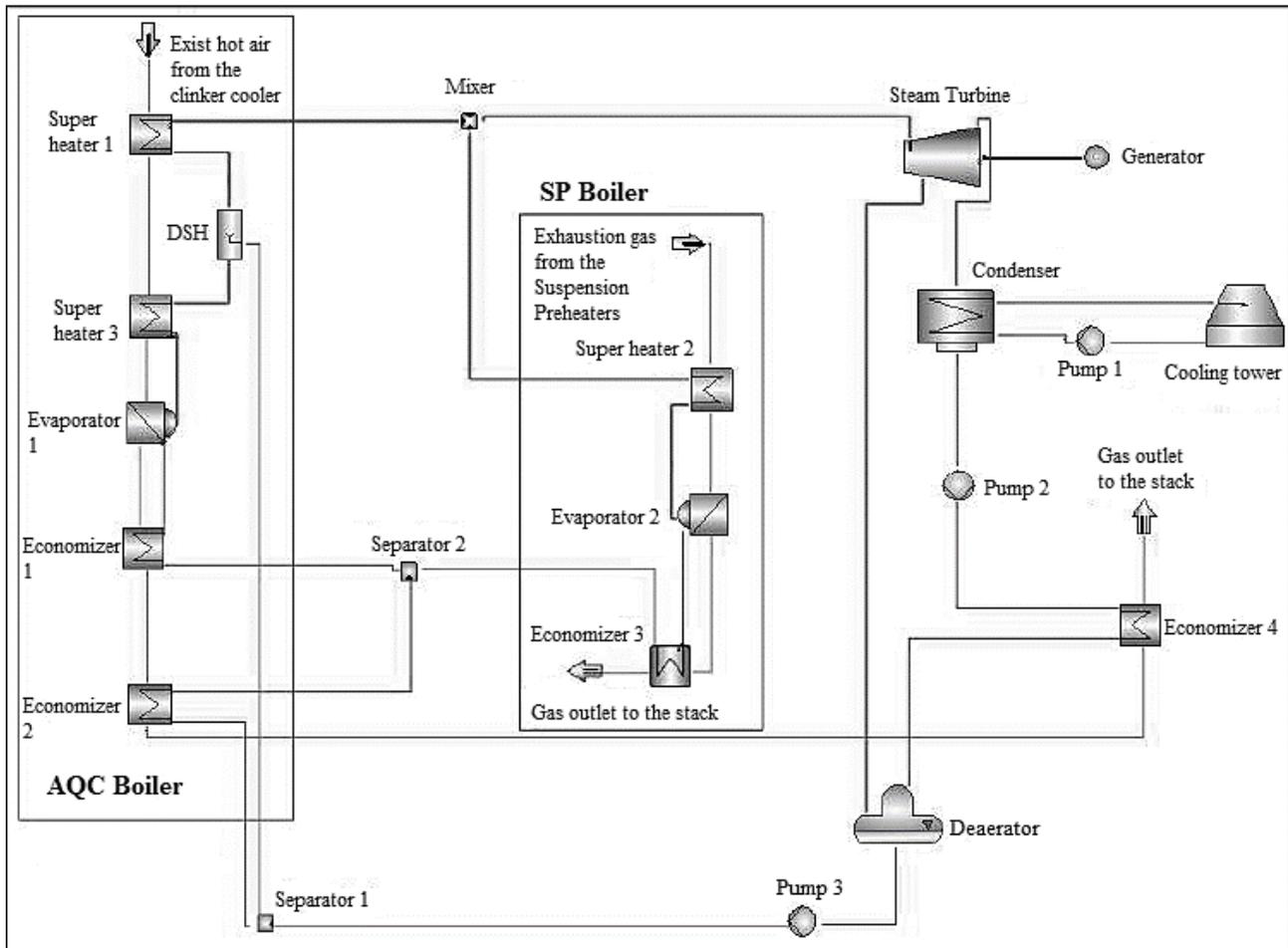


Figure 2. Schematic diagram of the actual Rankine cycle.

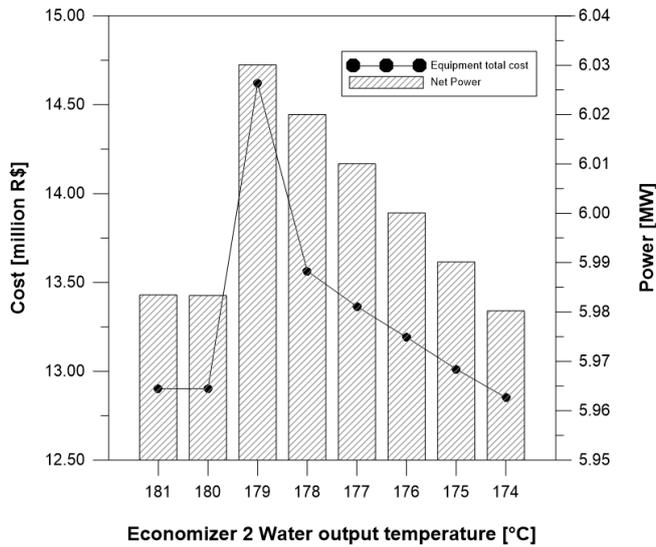
4. RESULTS AND DISCUSSION

The theoretical Rankine cycle generated 5.43 MW of electricity, recovering the waste heat of the Suspension Preheaters and the clinker cooler. This corresponds to 18 % of the Apodi plant energy demand.

The parameters of the actual Rankine cycle were changed to reduce the equipment cost without decreasing the cycle's final power.

The Figure 3a shows the results of net power generation and system cost as a function of the economizer 2. The output temperature range used in this analysis was 174 °C to 181 °C. For the temperature of 179 °C, the economizer 2 presented its highest net power and thermal effectiveness. To obtain these values, it was necessary to increase the surface area of the heat exchanger, which is directly linked to its final cost. That is because the total cost of the equipment was also maximum for this temperature.

The Figure 3b contains the superficial area and effectiveness according to the economizer 2 temperature values.



(A)

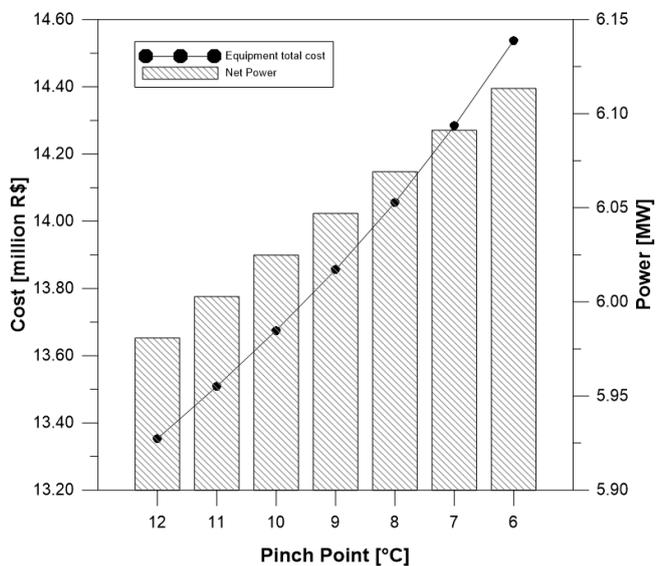
Water output temperature, °C	Heat Transfer surface area, m ²	Effectiveness, -
181	3,337.80	0.8281
180	3,337.80	0.8281
179	4,769.28	0.8810
178	4,384.93	0.8697
177	4,045.58	0.8584
176	3,753.03	0.8471
175	3,494.51	0.8358
174	3,266.69	0.8245

(B)

Figure 3. Influence of the water output temperature in the performance of Economizer 2.

The Figure 4a contains the cost and net power variation of the evaporation 2. These parameters were related to the pinch point of the heat exchanger, which ranged between 6 and 12 °C. The effectiveness of the heat exchanger increases with the reduction of its pinch point. For high effectiveness (above 95 %), the heat exchanger becomes big and very expensive.

The Figure 4b shows the superficial area and effectiveness obtained by varying the pinch point.



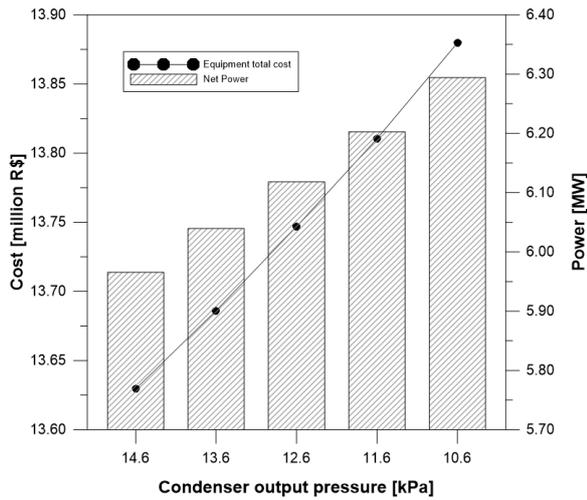
(A)

Pinch point, °C	Heat Transfer surface area, m ²	Effectiveness, -
12	4,720.15	0.8987
11	4,896.96	0.9071
10	5,090.75	0.9155
9	5,305.17	0.9239
8	5,545.10	0.9323
7	5,817.37	0.9407
6	6,130.84	0.9491

(B)

Figure 4. Influence of Pinch point in the performance of Evaporator 2.

The Figure 5a presents the cost and net power generated by the cycle as a function of the condenser outlet pressure. The range used for this parameter was 10.6 to 14.6 kPa. Lower pressures improve the net power generation however; they also result in a higher cost, once a higher vacuum production is required. The Figure 5b contains the superficial area of the condenser, by varying its output pressure.



(A)

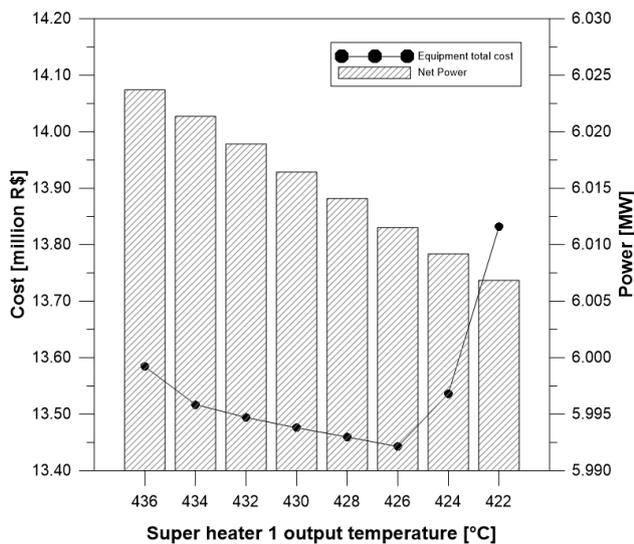
Output pressure, kPa	Heat Transfer surface area, m ²
14.6	253.32
13.6	265.72
12.6	280.37
11.6	298.01
10.6	319.75

(B)

Figure 5. Influence of output pressure in the performance of Condenser.

The Figures 6a and 7a present the cost and net power generated as a function of the super heaters output temperature. The temperature of super heater 1 varied between 422 and 436 °C and the temperature range of super heater 2 was 280 to 296 °C. The higher the outlet temperature of the super heater, the higher the enthalpy of the steam at the turbine inlet. In these cases, it is possible to generate more power and to reduce the total cost of the system despite the increase of the heat exchanger surface area. The lowest cost of super heater 1 was obtained around 426 °C, due to the smaller surface area of the heat exchanger. For the super heater 2, the optimum temperature was 290 °C. The Figures 6b and 7b show the results of superficial area and effectiveness for the super heaters 1 and 2.

Table 5 presents the best results of each equipment, considering its possible configuration limits. The parameters of the actual Rankine cycle were changed to reduce the equipment cost without decreasing the cycle's final power. The variation of the condenser output pressure and the economizer 2 water output temperature provided the lowest power generation costs, being 418.87 R\$/MWh and 416.37 R\$/MWh respectively. However, as the difference between these values isn't significant, the simulation with the highest power generation, in this case 6.29 MW, was chosen.

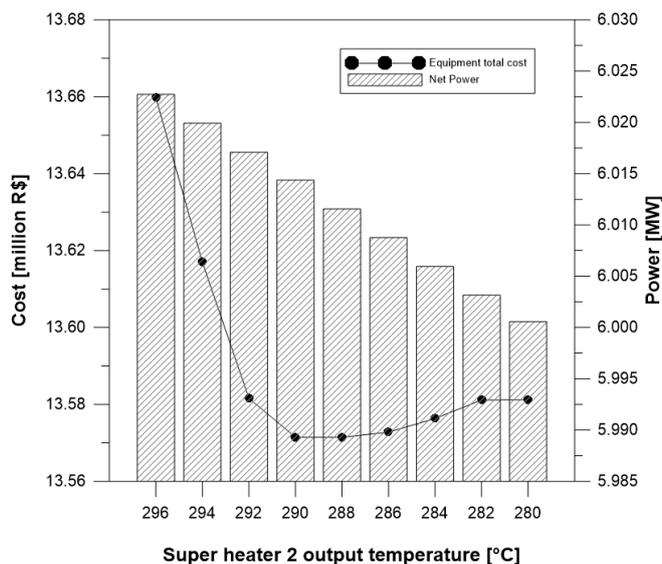


(A)

Output temperature, °C	Heat Transfer surface area, m ²	Effectiveness, -
436	584.85	0.8939
434	461.08	0.8337
432	375.50	0.7720
430	310.02	0.7088
428	257.01	0.6439
426	212.42	0.5772
424	173.94	0.5088
422	140.07	0.4385

(B)

Figure 6. Influence of output temperature in the performance super heater 1.



Output temperature, °C	Heat Transfer surface area, m ²	Effectiveness, -
296	639.36	0.9081
294	600.19	0.8935
292	566.27	0.8789
290	536.27	0.8643
288	509.39	0.8496
286	485.01	0.8349
284	462.69	0.8202
282	442.19	0.8055
280	423.09	0.7908

(A)

(B)

Figure 7. Influence of output temperature in the performance super heater 2.

Table 5. Optimized parameters for each cycle component.

Parameters	Super heater 2	Super heater 1	Condenser	Evaporator 2	Economizer 2
Output Temperature SH2, °C	290	-	-	-	-
Output Temperature SH1, °C	-	426	-	-	-
Output pressure COND, kPa	-	-	10.6	-	-
Pinch point EVAP2, °C	-	-	-	12	-
Water output temperature ECON2, °C	-	-	-	-	174
Net Power, MW	6.0144	6.0115	6.2942	5.9808	5.9802
Investment cost, R\$	56,457,361.73	55,921,467.50	57,739,755.38	55,549,336.57	53,463,367.52
Generation cost, R\$/MWh	421.16	420.25	418.87	420.09	416.37

A feasibility study was conducted to verify the possibility of implementation of the proposed system and its cost-benefit. The optimized plant presents a cost of R\$57.7 million and generates 6.29 MW that is equivalent to 21 % of its total energy demand. The Apodi plant operates 8030 h/year, so the cogeneration plant is able to produce 50.54 GWh/year. As this cement industry has an annual consumption of 132 GWh, the cogeneration plant is able to supply 38 % of its annual consumption.

According to the *Companhia Energética de Minas Gerais - CEMIG*, the cost of electricity for the industrial class is 430.74 R\$/MWh. By applying the optimized Rankine cycle at the Apodi plant, it is possible to save R\$21.7 million per year that, previously, were directed to CEMIG.

From this data and considering that the cogeneration plant has a useful life of 20 years, the feasibility of the system was determined.

The feasibility study showed that the cogeneration plant proposed presents an investment around R\$57.7 million and its payback time is about 3.3 years. In other words, this is the time it takes to pay off its initial investment.

5. CONCLUSIONS

The cogeneration plant installed in the Apodi plant in Fortaleza uses the waste gases from two sources of the cement manufacturing process, the Clinker Cooler and the Suspension Preheaters. The Rankine cycle was modelled and optimized with the GateCycleTM software. In the simulations performed, the parameters of each component of the cogeneration plant were varied, considering its configuration limits. The actual cycle was able to generate 6.29 MW of net power, that corresponds to 21 % of the factory's total demand.

Its investment cost, including equipment, transportation, and installation, was estimated at R\$ 57.7 million, and its payback time was calculated at 3.3 years, quite fast considering that the cogeneration plant's useful life is 20 years. Finally, the implementation of the optimized Rankine cycle generated annual savings of R\$ 21.7 million for the Apodi plant. This saving is due to the 38 % reduction in its energy costs from CEMIG.

6. ACKNOWLEDGEMENTS

The authors would like to express acknowledgements to FAPEMIG and Pontifical Catholic University of Minas Gerais for the financial support to elaborate this paper.

7. REFERENCES

- Amarasinghe, W.S., Husum, I., and Tokheim, L., 2018. "Waste heat availability in the raw meal department of a cement plant". *Case Studies in Thermal Engineering*, Vol. 11, pp. 1–14.
- Amiri, A., and Vaseghi, M.R., 2015. "Waste heat recovery power generation systems for cement production process". *IEEE Transactions on Industry Applications*, Vol. 51, No. 1, pp. 13–19.
- Atmaca, A., and Yumrutaş, R., 2014. "Thermodynamic and exergoeconomic analysis of a cement plant: Part II – Application". *Energy Conversion and Management*, Vol. 79, pp. 799–808.
- Engin, T., and Ari, V., 2005. "Energy auditing and recovery for dry type cement rotary kiln systems – A case study". *Energy Conversion and Management*, Vol. 46, pp. 551–562.
- GhalandarI, V., Majd, M.M., and Golestanian, A., 2019. "Energy audit for pyro-processing unit of a new generation cement plant and feasibility study for recovering waste heat: A case study". *Energy*, Vol. 173, pp. 833–843.
- Han, T., Wang C., Zhu, C., and Che, D., 2018. "Optimization of waste heat recovery power generation system for cement plant by combining pinch and exergy analysis methods". *Applied Thermal Engineering*, Vol. 140, pp. 334–340.
- Irungu, S.N., Muchiri, P., and Byiringiro, J.B., 2017. "The generation of power from a cement kiln waste gases: A case study of a plant in Kenya". *Energy Science and Engineering*, Vol. 5, No. 2, pp. 90–99.
- Loh, H.P., Lyons, J., and White, C.W., 2002. "Process Equipment Cost Estimation".
- Madlool, N.A., Saidur, R., Hossain, M.S., and Rahim, N.A., 2011. "A critical review on energy use and savings in the cement industries". *Renewable and Sustainable Energy Reviews*, Vol. 15, pp. 2042–2060.
- Mohammadi, A., Ashjari, M.A., and Sadreddini, A., 2018. "Exergy analysis and optimisation of waste heat recovery systems for cement plants". *International Journal of Sustainable Energy*, Vol. 37, No. 2, pp. 115–133.
- Nami, H., and Anvari-Moghaddam, A., 2020. "Small-scale CCHP systems for waste heat recovery from cement plants: Thermodynamic, sustainability and economic implications". *Energy*, Vol. 192, pp. 1–17.
- Pradeep Varma, G.V., and Srinivas, T., 2017. "Power-Augmented Steam Power Plant in a Cogeneration Cement Factory". *Journal of Energy Engineering*, Vol. 143, pp. 1–12.
- Rad, E.A., Mohammadi, S., 2018. "Energetic and exergetic optimized Rankine cycle for waste heat recovery in a cement factory". *Applied Thermal Engineering*, Vol. 132, pp. 410–422.
- Sanaye, S., Khakpaav, N., Chitsaz, A., Yahyanejad, M.H., Zolfaghari, M., 2020. "A comprehensive approach for designing, modeling and optimizing of waste heat recovery cycle and power generation system in a cement plant: A thermo-economic and environmental assessment". *Energy Conversion and Management*, Vol. 205, pp. 1–18.
- Tan, Y., Li, X., Zhao, L., Li, H., Yan, J., and Yu, Z., 2014. "Study on utilization of waste heat in cement plant". *Energy Procedia*, Vol. 61, pp. 455–458.
- Wang, J., Dai, Y., and Gao, L., 2009. "Exergy analyses and parametric optimizations for different cogeneration power plants in cement industry". *Applied Energy*, Vol. 86, pp. 941–948.
- Zeeshan M., and Arbab M.N., 2015. "Waste Heat Recovery and its Utilization for Electric Power Generation in Cement Industry". *International Journal of Engineering & Technology IJET-IJENS*, Vol. 15, No. 1, pp. 28–33.

8. RESPONSIBILITY NOTICE

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