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ANALYSIS OF THERMODYNAMIC CYCLES FOR COGENERATION IN CEMENT INDUSTRY

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Abstract. *This paper presents an analysis of thermodynamic cycles for cogeneration in cement industry. Three cycles are suitable for this process, conventional Rankine cycle (Single Flash and Dual Pressure), Organic Rankine Cycle and Kalina Cycle. Mathematic issues were developed using the Engineering Equation Solver (EES) software involving each cycle's efficiency and installation costs from China, Asia and Europe. Results show that the Kalina cycle is the one with the highest potential for cogeneration, with a maximum of 15.385 kW, in function of the cement process capacity, though it is also the one with the biggest cost for implementation, which is R$144,600,000.00. Therefore, energy cogeneration is a viable process, in which its application can reduce costs of electricity in the cement plant and reduce environment damage.*

Keywords: *cement kiln, cogeneration, Rankine cycle, organic Rankine cycle, Kalina cycle.*

1. INTRODUCTION

In cement industries three thermodynamic cycles can be used for cogeneration, conventional Rankine cycle (Dual-flash e Single-flash), Kalina cycle and Organic Rankine cycle. Although each cycle operates under different conditions and with different configurations, their components are the same. Thus, a reliability and availability analysis of their main components is also needed for cement cogeneration.

Considering a cement plant, the energy cogeneration proposal is to use the combustion gases from a cement kiln for steam and electric energy generation, using its thermic energy during the discharge in the atmosphere. When using cogeneration, it is possible to reach 87% efficiencies, in which provides great savings in the use of non-renewable resources and remarkable environments benefits.

At the moment that the risk of energy rationing increases in the country, the energy efficiency was the main subject during the Brazilian Congress of Energy Efficiency discussions on 2014, in São Paulo. Rodrigo Aguiar, president of the Brazilian Association of Energy Conservation Services Companies (Abesco), says that the importance of discussing about it is to unlink energy efficiency from energy rationing, "The energy efficiency is correlated to economy and competitively. The lack of an efficient program turns Brazil to waste, annually, the equivalent of half of the whole production from Usina de Itaipu for a year. An energy that could turn its way back to the system and be reused."

2. LITERATURE REVIEW

The convetional Rankine cycle, or just Rankine cycle, is a steam power cycle that has a pump, a steam generator, a turbine and a condenser, and according to Wang and others (2009), the efficiencies for the cycle's configurations, Single Flash and Dual-pressure steam, are, respectively, 25.7 and 24.9%. The Kalina cycle allows the use of residual heat under low temperature and has a mixture of water and ammonia as its working fluid, that guarantees a higher efficiency of the Kalina Cycle compared to the Rankine Cycle. Wagar and others (2010) developed a model to optimize the Rankine Cycle of ammonia-water, using ammonia concentrations between 0.0 and 0.5 and maximum system temperature between 75 and 350ºC, they had results for its efficiency between 25 and 35%. Wang and others (2009) imply that the cycle efficiency is 24.1%. And, according to Haglind (2015), the maximum energetic efficiency of the Kalina Cycle is between 15.87 and 37.1%. The Organic Rankine Cycle (ORC) presents higher efficiency, if compared to the conventional Rankine cycle using temperatures less than 300ºC. It works with organic fluids and, due to its lower evaporation heat and the simplicity of the turbines, since the reduced enthalpy difference during the expansion, the cycle presents a higher lifespan and lower maintenance costs. According to Wang and others (2009) the efficiency of the ORC is 20.6%. Tchanche and others (2011) analyzed the cycle operating in a maximum temperature between 250 and 400ºC and verified that it provides an efficiency that varies from 25 to 35%.

To investigate the cycles' efficiency it's necessary to analyze the reliability and availability of its components. Thus, the reliability of the boiler is a decisive factor to have a profitability of the unit and to ensure continued operation in high capacity factors, said so, IEA (2016) describes its reliability between 87 and 94% and A. F. Armor (2002) expresses the boiler availability as 85.5% and the boiler's feed pumps' as less than 98%. The availability and reliability of steam turbines are also important factor when analyzing a thermodynamic cycle, the better the availability and reliability from a given machine, the better will be its performance. The lifetime of a steam turbine is extremely high, if operated properly (including the chemistry control of the water from the boiler), steam turbines are reliable, requiring only annual revisions. According to chang and others (2000) the steam turbines availability and reliability are between 86.09 and 99.999%, and 84.8 and 97.3%, respectively.

3. METHODOLOGY

Three thermodynamic cycles were studied in order to evaluate their efficiencies and determine which one would be more beneficial to be used in cement cogeneration. Each process of each cycle are explained indicating how the main parameters of heat, work and energy transfer are determined

3.1 Conventional Rankine Cycle

In this cycle, Fig. 1, the most utilized working fluid is water, given its availability, non-toxic status, low cost and possibility of operation at medium temperatures.

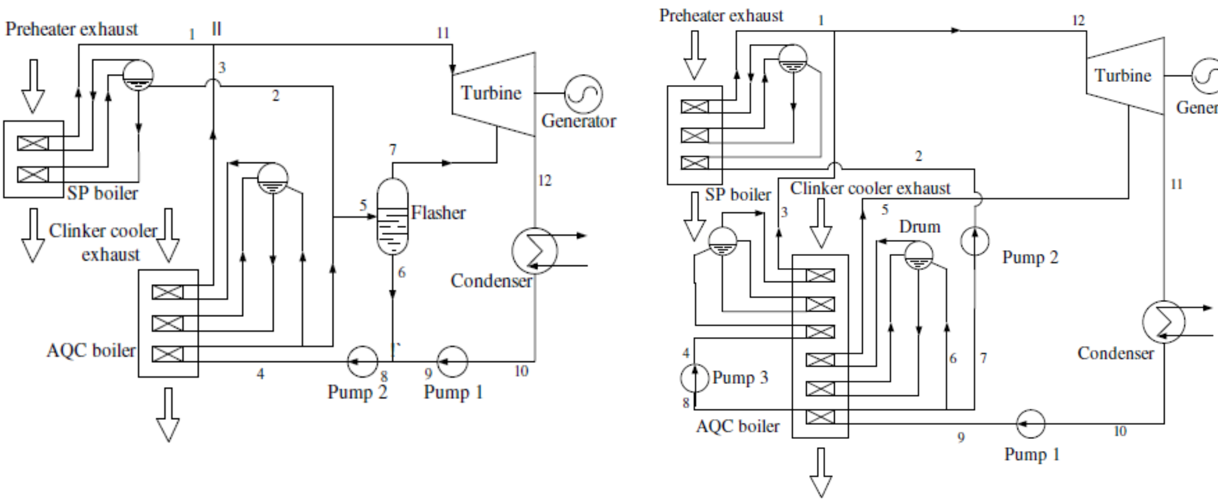
In the turbine' process the working fluid expands until reaching the pressure of the condenser. Through mass and energy balances the rate between work and mass unit is obtained:

In process thought the condenser, heat transfer from the fluid happens, at constant pressure, until saturated liquid. Through mass and energy balances the heat transfer heat is calculated:

In the pump the pressurization of the working fluid happens. The pump consumed power is calculated through mass and energy balances:

In the AQC and SP boilers heat inlet to the cycle. Through mass and energy balances, the heat transfer rate is calculated.

Lastly, the cycle thermal efficiency is calculated by the ratio between the net work of the cycle and its inlet heat.



Single flash steam cycle | Dual-Pressure steam cycle

Figure 1. Thermodynamic scheme of Rankine Cycle for cogeneration in cement industry (Wang *et all*, 2009)

3.2 Organic Rankine Cycle

In this cycle, Fig. 2, organic substance is used as working fluid due to the possibility of operation at medium and low temperatures. Several fluid could be studied for organic Rankine cycle application but, dry and isentropic are the most recommended. Between them, non toxics and environmental friendly are indeicated, for example, R123, R141b. The operational principle of the organic Rankine cycle similar to de conventional Ranike cycle.

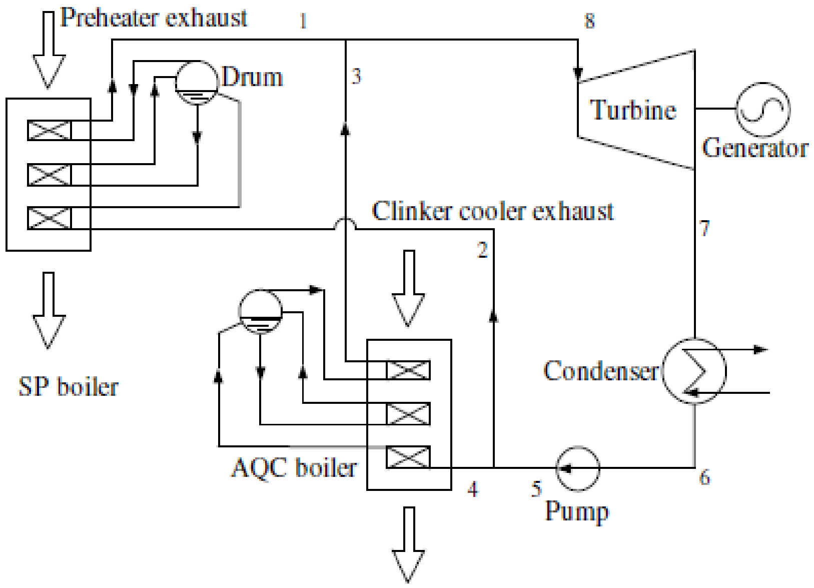


Figure 2. Thermodynamic scheme of Organic Rankine Cycle (Wang *et all*, 2009)

3.3 Kalina Cycle

In this cycle, fig. 3, the binary ammonia – water mixture is used as working fluid due to the possibility of operation at medium and low temperatures. Several Kalina cycle thermal scheme are suggested for cogeneration in cement industry. The Kalina cycle thermal scheme differs of the Rankine cycle in the condensation – destilaiton system, which is located after the turbne and before de boilers. This system is necessary to the adequation of the ammonia – water mixture concentration in order to maximize the cycle performance. Except for the condensation and destilation system, the operational principle of the Kalina cycle similar to de conventional Ranike cycle.

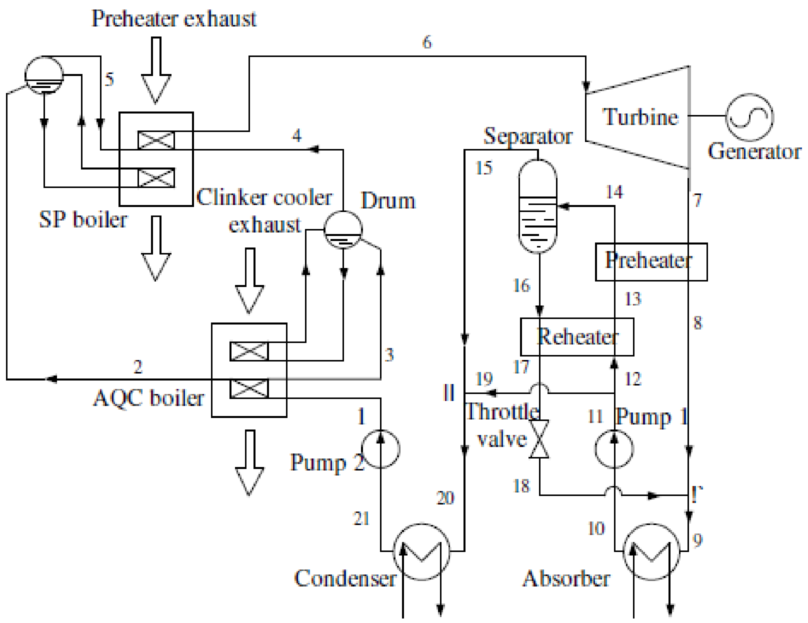


Figure 3. Thermodynamic scheme of Kalina Cycle (Wang *et all*, 2009)

3.4 Cement Cogeneration

Cogeneration occurs by the generation of electric or mechanical energy and thermal energy through the burning of a fuel (Nozomu et al., 2016). Cogeneration plants can reach 87% efficiency, which provides great savings in the use of a non-renewable resource, with notable benefits for the environment (ALCOOLbrás magazine, 2006).

While in Brazil there are about 90,000 MW of installed capacity and, of the total of electricity produced, only 4% is cogenerated energy, in Canada, China, Germany and the United States the percentage of cogenerated energy varies between 8% and 11%. The Netherlands has 20%, Denmark 27.5% and Russia 30% of electricity provided by cogeneration plants (BRUZADIN, 2009).

The cement manufacturing process requires high energy consumption, according to EPE (2013), more than 80% refers to the consumption of thermal energy during the burning of the fuels for the production of clinker. Therefore, the cement industry is responsible for large environmental impacts in the anthropic, biotic and physical environment, which are mainly caused by the emission of polluting gases from this burning (WBCSD, 2009). Figure 4 illustrates the process of cement production.

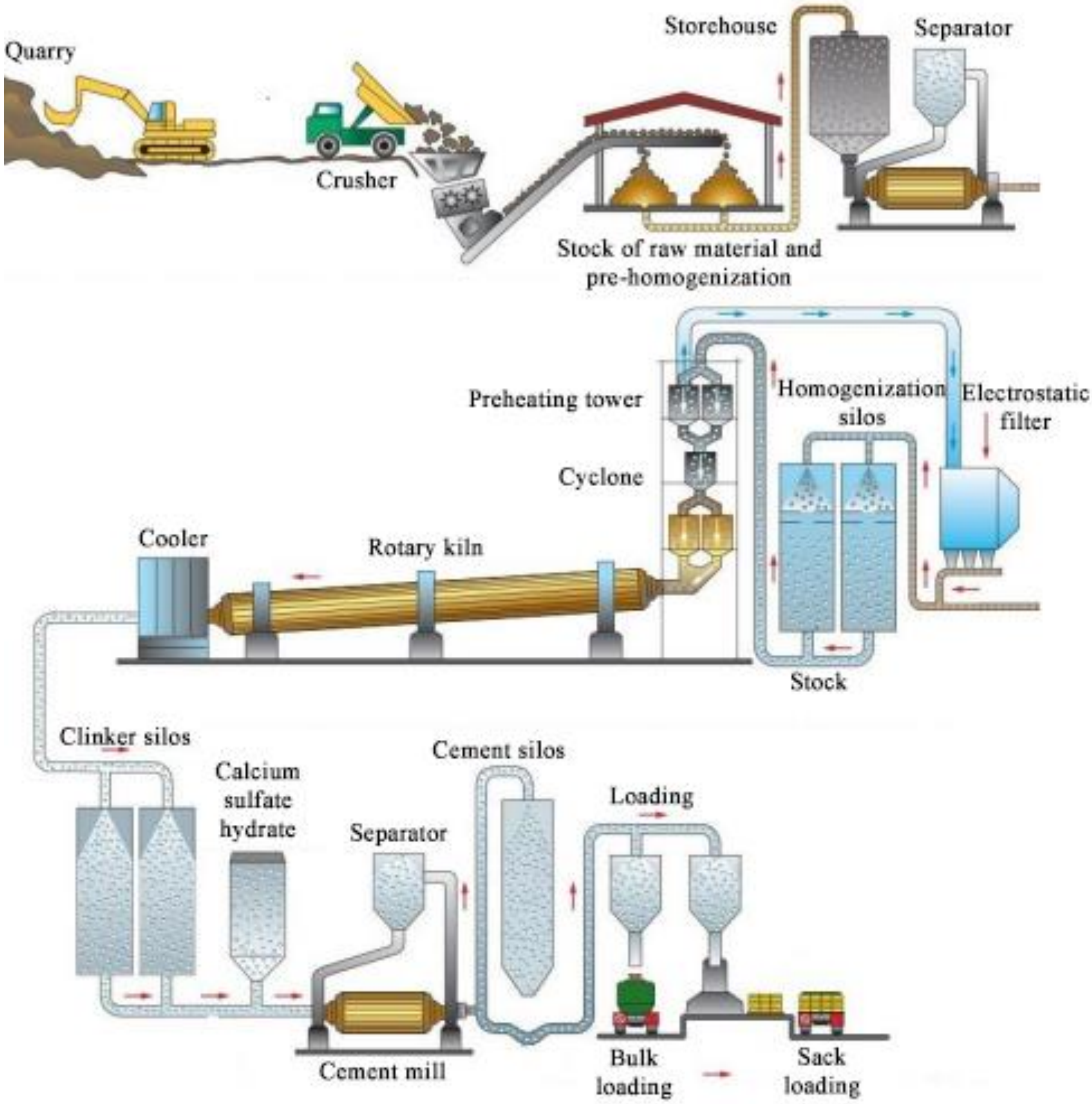


Figure 4. Basic flow of cement production (Galhardo, 2014)

3.5 Cement process information

In Tab. 1 the cement process information is presented as function of the dayly clinker capacity. The information included the temperature and mass flow of the flue gas at the preheater and clinker exhaust respectively. As can be see the preheater exhaust temperature is in the range of 300-400°C aproximatelly, which is in dependence of number of cyclone stages in the preheating tower. On the other hand the mass flow at the preheater outlet rise proportionally to the clinker production capacity. For the clinker cooler exhaust flue gas the temperature adopts values as function of the specifications of the process, in general in dependence of the cooler fan existing in the cement plant. It is possible to note that higher capacity of the fan (high mass flow) is less the clinker cooler exhaust temperature.

Table 1. Cement process information

		Preheater exhaust		**Clinker cooler exhaust**	
Source	Production capacity [tc/day]	Temperature [°C]	Mass flow [kg/s]	Temperature [°C]	Mass flow [kg/s]
Mirolli (2006)	3,000	385	76.50	360	33.16
ECRA (2009)	3,000	375	76.71	280	57.53
Apodi (2016)	3,500	310	88.00	440	48.10
Sui (2014)	4,500	315	113.20	204	56.25
Wang, Dai e Gao (2009)	5,000	340	126.70	310	86.20
Kalex (2010)	6,300*	340	159.00	300	126.10

* Estimated from the other capacities considering the regular increasing as function of the capacity.

3.6 Cost estimation

The Magazine Waste heat recovery for the cement sector: market and supplier analysis (2014) shows a graph that compares the installation costs of produced equipment in Asia, Europe and China, as shown in Fig. 5. In this figure de specific installation cost is shown for different regions of the world. According to this information the installation cost increase as function of the costs of the local scope of cycle equipment around the world. This information, toghether with the thermal efficiency was used to calculate the costs of installation of six different cement plant as shown latter.

The costs of implementation of cement cogeneration were calculated using the three thermodynamic cycles: Rankine Cycle (Single Flash and Dual Pressure), Organic Rankine Cycle and Kaline Cycle. The data used was provided by a study by Wang et al. (2009) and the chosen combustion gas for the cement plant was air (with specific heat, at constant pressure, of 1.005 kJ/kg°C).

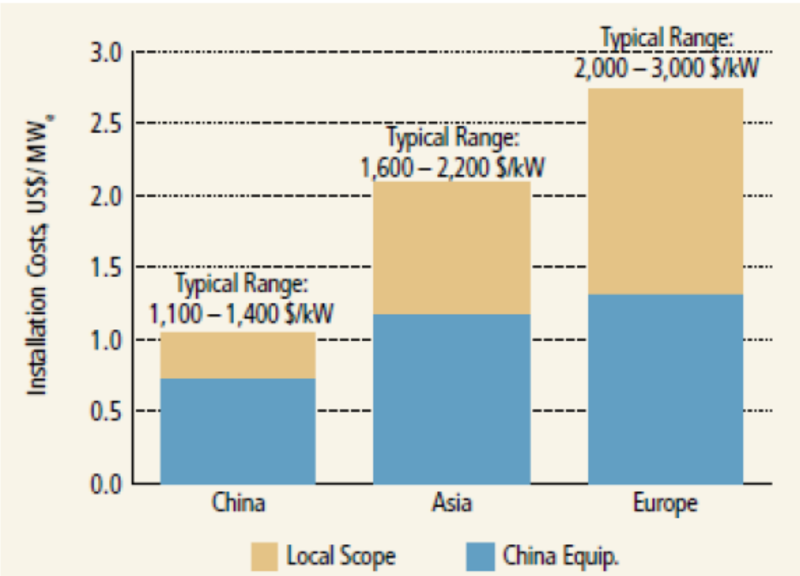


Figure 5. Installation costs of produced equipment in Asia, Europe and China for recovery residual heat (IFC, 2014)

3.7 Net power estimation

The available thermal energy from the preheater exhaust is estimated as:

$$Q_{PH} = m_{PH} \cdot c_p \cdot \left(T_{PH} - T_{stack\_PH}\right) \quad (1)$$

Where:
Q_{PH} is the available thermal energy from the preheater, in kJ/s;
m_{PH} is the flue gas flow from the preheater, in kg/s;
c_p is specific heat at the constant pressure of the flue gas in kJ/kg°C;
T_{PH} is the temperature of the flue gas in the preheater, in °C;
T_{stack_PH} is the stack temperature of the flue gas at the SP Boiler outlet, adopted in 280°C.

The same analysis can be made to calculate the available thermal energy from the clinker cooler exhaust:

$$Q_{CC} = m_{CC} \cdot c_p \cdot \left(T_{CC} - T_{stack\_CC}\right) \quad (2)$$

Where:
Q_{CC} is the available thermal energy from the clinker cooler exhaust, in kJ/s;
m_{CC} is the flue gas flow from the clinker cooler exhaust, in kg/s;
c_p is specific heat at the constant pressure of the flue gas in kJ/kg°C;
T_{CC} is the temperature of the flue gas in the clinker cooler exhaust, in °C;
T_{stack_CC} is the stack temperature of the flue gas at the AQC Boiler outlet, adopted in 114°C.

The total available thermal energy for cogeneration is the sum of the available energies calculated previously. So:

$$Q_{TOTAL} = Q_{PH} + Q_{CC} \quad (3)$$

Where:
Q_{TOTAL} is the total available thermal energy for cogeneration, in kJ/s.

As the thermodynamic cycle used for heat recovery has an efficiency, the output power is given by:

$$W = \eta \cdot Q_{TOTAL} \quad (4)$$

Where:
W is the net power out put from cogeneration, in kW.

4. RESULTS AND DISCUSSION

Since the data provided in Fig. 5 presents the costs in American dollar, the exchange rate used was 3.133 R$/US$ (exchange rate from 24/03/2017). Table 2 and 3 present cogeneration estimation and cost estimation, respectively, in relation to production capacity (ton clinker/day) of the cement plants.

Table 2. Cogeneration estimation

Production capacity (tc/day)	Cogeneration potential (kW)					
	Rankine		Organic Rankine		Kalina	
	Single Flash	Dual Pressure	Minimum	Maximum	Minimum	Maximum
3000 (Mirolli, 2006)	6,256	6,062	5,015	8,520	3,863	9,032
3000 (ECRA, 2009)	5,379	5,212	4,312	7,326	3,322	7,765
3500 (Apodi, 2016)	10,658	10,326	8,543	14,514	6,581	15,385
4500 (Sui, 2014)	5,209	5,047	4,175	7,094	3,217	7,520
5000 (Wang, 2009)	5,827	5,646	4,671	7,936	3,598	8,412
6300 (Kalex LLC, 2010)	8,248	7,991	6,611	11,232	5,093	11,906

Table 3. Estimation of minimum and maximum costs of installation for cogeneration

Production capacity (tc/day)	Installation cost (MR$)					
	Minimum cost			Maximum cost		
	Chinese	Asian	European	Chinese	Asian	European
3000 (Mirolli, 2006)	13.31	19.37	24.21	39.61	62.25	84.89
3000 (ECRA, 2009)	11.45	16.65	20.81	34.06	53.52	72.99
3500 (Apodi, 2016)	22.68	32.99	41.24	67.48	106.00	144.60
4500 (Sui, 2014)	11.09	16.12	20.16	32.98	51.83	70.68
5000 (Wang, 2009)	12.40	18.04	22.55	36.90	57.98	79.06
6300 (Kalex LLC, 2010)	17.55	25.53	31.91	52.22	82.06	111.90

After calculations and analysis of the tables above, it's possible to observe that for all cement plant models the cycle with the highest potential for cogeneration is the Kalina cycle, when considering its maximum efficiency of 37.1%. The Organic Rankine cycle, with an efficiency of 35%, also obtained similar results.

Due to its higher potential of cogeneration, the Kalina cycle is also the one with the highest installation cost, R$144,600,000.00 for 37.1% efficiency in the Apodi (2016) model. But, proportionally to its efficiency, it also has the lesser cost when considering its minimum efficiency of 15.87%.

5. CONCLUSIONS

Based on the obtained results it's possible to conclude that cement cogeneration is a viable process, able to provide a maximum of about 15.000 kW when utilizing the Kalina cycle with its maximum efficiency.

Besides reducing costs with electricity provided by external sources, the cogenerated energy also helps reducing environmental impact caused by cement industries, given that the heat generated by them that was formerly discarded will be utilized in energy production instead.

6. ACKNOWLEDGEMENTS

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