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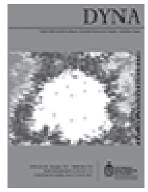

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Using waste energy from the Organic Rankine Cycle cogeneration in the Portland cement industry

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Received: June 16th, 2014. Received in revised form: September 13th, 2015. Accepted: October 25th, 2015.

Abstract
Cement production is intensive in terms of energy consumption. An analysis of the resources involved in manufacturing clinker needs a corresponding mass and energy balance. This balance may indicate the existence of residual heat flows that are not used. This paper summarizes the development of a protocol for the evaluation of a cement plant rotary kiln to implement an Organic Rankine Cycle (ORC) system for cogeneration. The results show that 19.2% of the energy preheater exhaust gas can be recovered to be used in producing 5.5 GWh/year of electricity and 23.7 GWh/year of thermal energy in the cement plant. The electricity generated would represent annual savings of 1.18 $/t cement. The thermal energy produced in cogeneration, equivalent to coal in the plant itself, represents cement savings of 0.51 $/t cement and emissions reductions of 8 kt CO_2/year.

Keywords: energy balance; heat recovery; Portland cement; Organic Rankine Cycle (ORC).

Aprovechamiento del calor residual por cogeneración con Ciclo Rankine Orgánico en la industria del cemento Portland

Resumen
La producción de cemento es intensiva en consumo de energía. Un análisis de los recursos involucrados en la fabricación del clinker requiere de su correspondiente balance de materia y energía. Este balance puede indicar la existencia de flujos de calor residual que no son aprovechados. Este trabajo resume el desarrollo de un protocolo de evaluación de un horno rotatorio de planta cementera para la implementación de un sistema Ciclo Orgánico de Rankine (ORC) para cogeneración. Los resultados permiten la recuperación de 19.2% de la energía del gas de escape del precalentador para su aprovechamiento en la producción de 5.5 GWh/año de electricidad y 23.7 GWh/año de energía térmica en la planta de cemento. La electricidad generada supondría un ahorro anual de 1.18 $/t cemento. La energía térmica producida, equivalente al carbón de la planta, supone un ahorro de 0.51 $/t cemento y una reducción de emisiones de 8 kt CO_2/año.

Palabras clave: balance de energía; recuperación de calor; Cemento Portland; Ciclo Orgánico de Rankine (ORC).

1. Introduction

1.1. Paper size, margins, columns and paragraphs

Cement is essential within the current economic development, but it requires large quantities of resources. Portland cement manufacturing is one of the most costly processes in the production of non-metallic minerals, in terms of energy consumption, as its production costs are above 25% [1,2]. Theoretically, this activity requires a minimum of 1.6 GJ to produce a tonne of clinker [3]. Added to this are the CO_2 emissions resulting from the use of fossil fuels, necessary for the calcination process and the emissions from the limestone decarbonation. This means that the cement sector is responsible for about 5% of the total anthropogenic CO_2 emissions [4].

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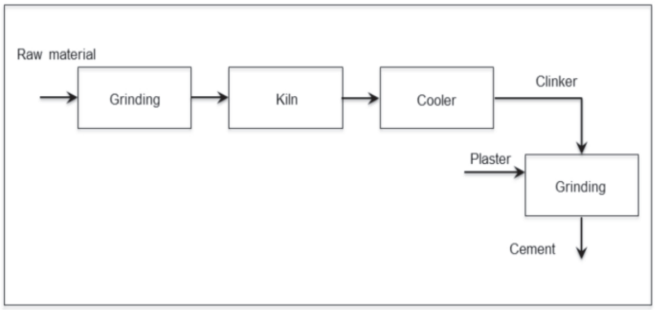

Figure 1. Diagram of the Portland cement manufacturing process.
Source: The authors.

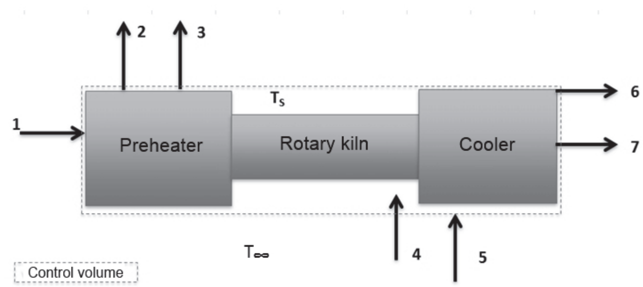

Figure 2. Control volume.
Source: The authors.

A number of studies have been carried out to evaluate Portland cement manufacturing´s energy consumption and CO_2 emissions [5-7], due to the growing interest in energy efficiency in the cement industry [3,8]. The high cost of energy makes it necessary to perform audits to analyze the possibilities of reducing the consumption in the clinker production process [9]. The study of mass and energy flows allows the possibilities of recovery of the residual heat [10-12] to be analyzed, which is recognized as a potential means to improve energy efficiency in the cement manufacturing process.

The Organic Rankine Cycle (ORC) is commonly accepted as a viable technology to convert heat at low temperature to electricity. Further benefits include low maintenance, favorable operating pressures and autonomous operation [13]. Having been proven in other industries, the interest in the ORC is increasing in the cement industry due to the fact that improvements in clinker production have led to lower exhaust gas temperatures [14].

The analysis of mass and energy balances of a typical rotary kiln cement plant is performed in this paper. The objectives are to evaluate the mass and energy balances in the cement plant, in order to determine the overall energy efficiency of the process and to enable their recovery by installing an ORC plant cogeneration system.

2. Process description and data collection

A dry process Portland cement production plant with a production capacity of about 1.7 kt/day has been chosen as a reference. The rotary kiln is located in the intermediate part of the production process; this can be seen in Fig. 1

The assessed oven has a cylindrical tubular geometry, measuring about 3.5 m x 54 m; it is longitudinally inclined with a slope of about 1º. It is lined with refractory brick inside and it is made of steel outside. The assembly rotates at a speed of about 30 rpm. In the kiln, the raw material is heated up to 1450 °C in such a way that it reacts to form clinker (a mixture of calcium silicates and aluminates). The process requires the introduction of air so that it operates with an excess of oxygen, otherwise there may be deficiencies, either by the formation of other phases or by incomplete formation of the components [15].

Due to the complexity of cement production [16] and energy flows that occur around the rotary kiln, a number of considerations were contemplated:

- Raw material, fuel and slag create a constant chemical composition.
- There is loss of negligible air.
- There are constant average ambient temperatures ($T\infty$ = 303 K), kiln surface (Ts = 581 K), cooler surface (Ts = 353 K) and preheater surface (Ts = 348 K).
- Combustion is complete.
- The operation is undertaken at a steady state and there are equilibrium conditions.

The methodology used follows these steps:

1) Definition of the control volume.
2) Identification and characterization of the main flows.
3) Formulation of mass balance.
4) Formulation of energy balance

2.1. Control volume

The control volume includes a preheater, a rotary kiln and a clinker cooler, Fig. 2

Where:

5) Raw material.
6) Preheater exhaust gas.
7) Preheater dust.
8) Coal.
9) Cooling air.
10) Clinker.
11) Cooler hot air.

2.2. Identification and characterization of the main mass flows

The inflow is the raw material in the control volume preheater (1); the raw material in the rotary kiln is the fuel (4) and, in the cooler, it is the air (5), Fig. 2.

The composition of the raw materials, the fuel (coal in this case), the clinker and the preheater exhaust gas are shown in Tables 1-4, respectively.

Table 1.
Composition of raw material.

Component	Percentage (%)
CaO	68.58
SiO_2	19.78
Al_2O_3	4.91
Fe_2O_3	4.04
MgO	2.69

Source: The authors.

Table 2.
Composition of coal.

Component	Percentage (%)
C	68.60
O	7.19
H	4.39
N	1.59
S	1.11
Ash	17.12

Source: The authors.

Table 3.
Composition of clinker.

Component	Percentage (%)
CaO	66.97
SiO_2	21.66
Al_2O_3	4.82
Fe_2O_3	4.04
MgO	2.51

Source: The authors.

Table 4.
Composition of preheater exhaust gas.

Component	Percentage (%)
N_2	60.54
CO_2	22.74
H_2O	10.03
O_2	6.69

Source: The authors.

2.3. Mass balance

The following reactions produced in the system must be considered, eq. (1-5).

- Calcination:

$$CaCO_3 \rightarrow CaO + CO_2 \quad (1)$$

$$MgCO_3 \rightarrow MgO + CO_2 \quad (2)$$

- Combustion:

$$C + O_2 \rightarrow CO_2 \quad (3)$$

$$2H_2 + O_2 \rightarrow 2H_2O \quad (4)$$

$$S + O_2 \rightarrow SO_2 \quad (5)$$

The main component of the gas produced is CO_2, which is derived from the combustion and decarbonation reactions. It is considered that, to manufacture cement, about half of the CO_2 emissions come from combustion and the other half are produced in the decomposition of the calcium carbonate in clinker production [17]. Only traces of SO_2 are present due to the combustion of the fuel sulphur. In the final part of the cement producing process, approximately 5% gypsum is added to the clinker.

2.4. Energy balance

The energy balance uses the physical data and equations described in the Peray manual [18]; these have been used in several papers about mass and energy balances in cement plants [1,11,19]. The first step is to carry out a balance of the enthalpy variation flows. To do this, both the temperature and calorific value of the fuel (28,000 kJ/kg) are characterized.

The results are presented as percentage of the total energy released by combustion of fuel in the kiln.

Table 5.
Mass balance.

Flow	Mass (kg/s)	Temperature (ºC)
1	29.61	70
2	57.11	330
3	2.50	159
4	4.25	70
5	67.86	30
6	18.36	130
7	23.75	215

Source: The authors.

Table 6.
Input energy flows.

Description	Result (kJ/kg-clinker)	Distribution (%)
Coal combustion	3,612	94.01
Raw material heat	102	2.65
Cooling air heat	98	2.55
Raw material Organics	19	0.49
Coal sensible heat	11	0.29
Total heat input	**3,842**	**100.00**

Source: The authors.

Table 7.
Output energy flows.

Description	Result (kJ/kg-clinker)	Distribution (%)
Clinker formation	1,783	46.41
Preheater exhaust gas	1,100	28.63
Cooler hot air	285	7.42
Heat losses by radiation from the kiln surface	155	4.03
Clinker discharge	90	2.34
(1)Heat losses by convection from the kiln surface	54	1.41
Heat losses by dust from the electrofilter	37	0.96
Moisture in the raw material and coal	28	0.73
Heat losses due to preheater surface radiation	2	0.05
(2)Heat losses due to preheater surface convection	2	0.05
Heat losses from cooler surface radiation	1	0.03
(2) Heat losses from cooler surface convection	1	0.03
Unaccounted losses	304	7.91
Total heat output	**3,842**	**100.00**

Note: Churchill & Bernstein(1) and Saunders & Weise(2) equations were used [19]. The starting point was the evaluation of the characteristics and operating conditions of every piece of industrial equipment used in the process.
Source: The authors.

3. Results and Discussion

The results of the mass balance are shown in Table 5.

The heat flows described have been considered for the energy balance. It is important to note that the moisture content in the raw materials due to energetic potential may be affected. The calculations have been made considering amounts per kg

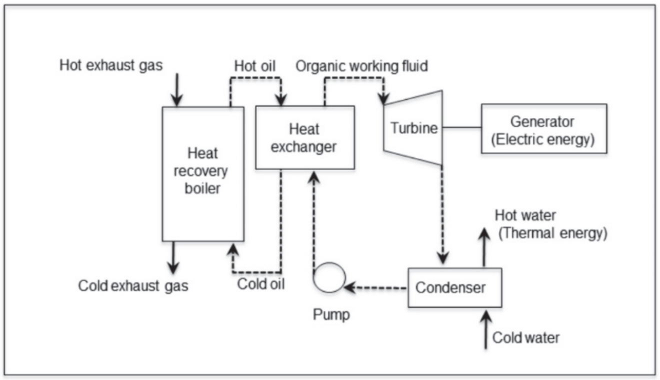

Figure 3. ORC cogeneration scheme.
Source: The authors.

of produced clinker. Tables 6 and 7 show the results of the energy balance for the different flows.

Energy recovery in cement plants has been studied in different works [10,11,21], as has the importance of ORC as an energy production system [22,23] and the use of cogeneration systems in the industry [1,24]. According to the results, (Table 7), there are opportunities for residual heat flow energy recovery. Thus, emissions and heat loss into the environment would be avoided. The largest residual heat flow corresponds to the preheater exhaust gas, which reaches 330 ºC, accounting for 53.4% of total losses. Part of this flow can be recovered by an ORC cogeneration system, Fig. 3

The proposed cogeneration system is shown in Fig. 3. The energy is transferred from the preheater exhaust gas to the organic fluid, used in the system's Rankine cycle, by means of a thermal oil. The circuit operates with a minimum temperature of 250 °C, which, to prevent intensive modifications to the plant, comes from the preheater exhaust gas at the outlet of the heat exchanger. The system allows it to be used as thermal energy for the hot water leaving the condenser manufacturing process. According to the final temperatures and operating conditions, it is possible to calculate the total available thermal energy ($\dot{Q}_T$) from the preheater exhaust gas mass flow ($\dot{m}_2$) [25], eq. (6).

$$\dot{Q}_T = \dot{m}_2 \cdot \left(h_{\text{Hot exhaust gas (330ºC)}} - h_{\text{Cold exhaust gas (250ºC)}} \right) \quad (6)$$

$$\dot{Q}_T = 57.11\ \text{kg/s} \cdot (610.4 - 527.0)\ \text{kJ/kg} = 4{,}763\ \text{kW}$$

In order to determine the power of the electric generator, an overall efficiency (η) of 85% is estimated for the recovery of heat in this flow by the cogeneration ORC process ($\dot{Q}_{ORC}$), eq. (7)[26].

$$\dot{Q}_{ORC} = \eta \cdot \dot{Q}_T = 4{,}049\ \text{kW} \quad (7)$$

Considering that 18% of the recovered energy can be transformed into electricity, it is possible to achieve a power of 729 kW [26]. 7,500 operating hours per year at the plant would allow energy savings of 5.5 GWh/year. Taking energy costs to be 0.13 $/kWh [27] the value of such energy savings would amount to 1.18 $/t cement.

A preliminary estimation of the costs associated with the implementation of the ORC cogeneration system would need to include the necessary equipment and installation expenses. The investment and profitability significantly depend on the location and size of the ORC plant. For the whole system (Fig. 3) a 3 million dollar budget is estimated, which includes shipping, installation and commissioning. Therefore, an estimate of the period of a simple return on investment (p) can be shown in eq. (8).

$$p = (\text{Implementation costs})/(\text{Annual savings}) \quad (8)$$

$$p = (3 \cdot 10^6\ \$)/(0.72 \cdot 10^6\ \$/\text{year}) = 4.2\ \text{years}$$

It was calculated that 82% of the unused energy for electricity production is available for thermal use. If 4% of it is deducted due to heat losses in the system, the remaining 78% can be collected in hot water at 80 °C at the condenser outlet, which is equivalent to 23.7 GWh per year. This thermal energy, calculated annually, is equivalent to about 3 kt/year of coal used at the plant at a cost of 100 $/t [27], which represents about 0.31 million dollars. The use of this energy is equivalent to 8 kt CO_2 annual emissions. However, the particular characteristics of each plant, due to economic, environmental and technical factors, determine the viability of these types of projects.

Energy savings, through using an ORC cogeneration system, would also improve the energy efficiency of the plant. It should be noted that these calculations might vary according to the plant operating conditions and other economic factors.

4. Conclusions

The proposed methodology can be quickly applied to any cement plant with a rotary kiln that is used as a first assessment. The results of the audit, depending on the input and output thermal energy, indicate that the clinker production system has an efficiency of 46.4%. The main heat losses that occur in the kiln are with the preheater exhaust gas (28.6%), the hot air from the cooler (7.4%) and in radiation and convection (5.6%).

Recovering waste heat from the preheater exhaust gas flow is feasible and can provide about 0.7 MW of electric power, by using an ORC cogeneration system. The results obtained would allow the recovery of 19.2% from the preheater exhaust gas energy to produce 5.5 GWh/year of electricity and 23.7 GWh/year of thermal energy.

The use of the electricity generated in cogeneration would save about 0.72 million dollars per year (1.18 $/t cement). The equivalent in thermal energy, in terms of coal used by the plant itself, represents a cost of 0.31 million dollars (0.51 $/t cement) and would avoid 8 kt/year of CO_2 emissions. The expected payback period for the investment in the proposed facility is 4.2 years.

Acknowledgement

Adriana Marcela Osorio Correa and Gloria Restrepo are grateful to COLCIENCIAS and the Sustainability Strategy Program 2013-2014 of Antioquía University (Colombia).

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