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Cement Industrial Process: Modeling and Optimization of the Specific Electrical Energy of Cement Crusher

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ABSTRACT: *Cement production has been one of the most energy intensive industries in the world with energy typically accounting about 50–60% of the production costs. Reduction of the production cost is very much important. Grinding is the largest electricity consumer in the cement industry. It's up to 70% of the total electrical energy in the cement industry. In this paper, the specific electrical energy (CEES) of the cement crusher has been modeled and optimized as a function of feed flow, separator speed and air flow using the experimental design method. The validation of the developed model was verified. The results confirm that the proposal model provided a satisfactory fit to the experimental data. The results also show that the increase in the feed flowresults in a decrease in the specific electrical energy, while the increase in the air flow and the separator speed causes a specific electrical energy increase. Excel solver based on a simplex optimization algorithm helped in reaching the global optimal solution for minimizing the specific electrical energy of the cement crusher.*

Keywords -*cement crusher, cement production,experimental design,specific electrical energy, modeling*

I. INTRODUCTION

During these last two decades, great interest was dedicated to the subjects of environmental preservation and energy resources management. These highly discussed topics are usually found at the top of the international political agenda because of their tremendous significance for the next generations [1-2]. In this context, the government of Morocco developed a national energy strategy to control energy consumption in different sectors with the goal of saving 12% in 2020 and 15% in 2030 [3]. Among the entire energy intensive sector, industry consumes for nearly 21% of Moroccan final energy consumption. The majority of Moroccan industrial energy consumption comes from the cement industry which consumes the lion's share with about 30 %, while steel industry represents 22%; and chemistry has shown 16 % (see Figure 1)[4]. In a high energy consumption sector as the production of cement, it is essential to accurately monitor its consumptions, and to adapt its production to fluctuations in energy markets by opting for the energy efficiency which is currently considered as a fourth energy source after fossil fuels, renewable energy and nuclear energy [5-6].

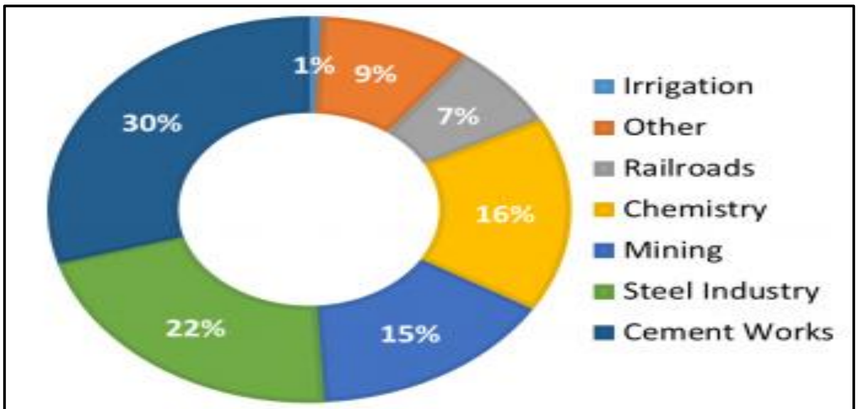

Figure 1: Amount of energy used by each industrial sector [4].

Cement production is at the heart of the construction industry. It is an economic indicator, linked on the one hand to the number of inhabitants, and on the other hand to the growth of each country over a given period [8]. Demand for cement has increased significantly as a result of rapid growth in the construction sector worldwide, particularly as a result of the higher increase in the construction for emerging countries.

The cement industry is one of Morocco's most highly energy intensive economic sectors, in which energy represents 50–60% of the total production costs [9]. The production of cement clinker from limestone and chalk is the main energy consuming process in this industry. The most widely used cement type is Portland cement, which contains 95% cement clinker. Table 1 represents composition of different cement types. Most of the energy used is in the form of fuel for the production of cement clinker and electricity for grinding the raw materials and finished cement. Thermal energy accounts for about 20–25% of the cement production cost [10]. The typical electrical energy consumption of a modern cement plant is about 110–120 kWh per ton of cement [11]. Grinding is the largest electricity consumer in the cement industry. It's up to 70% of the total electrical energy in the cement industry [12]. Optimizing the grinding process is important to make finer cement products, reduce energy consumption and greenhouse gas emissions.

Table 1: Composition of different cement types [13].

Cement type	Portland cement (%)	Portland fly-ash cement	Blast furnace cement (%)	Active slag cement (%)
Clinker	95	75	30	-
Fly ash	-	25	-	45
Blast furnace slag	-	-	65	-
Synthetic slag	-	-	-	45
Quicklime	-	-	-	-
Water glass	-	-	-	10
Sodium sulphate	-	-	-	-
Gypsum	5	-	5	-

In this context, the main objective of this paper is to model and optimize the specific electrical energy (CEES) of the cement crusher as a function of feed flow, separator speed and air flow using the experimental design method.

II. EXPERIMENTAL SECTION

The crusher specific electrical energy represents the energy consumed by the different elements of the crusher to produce a ton of cement. The major equipment that consume electrical energy at the cement crusher are: main engine with a power of about 4000 Kw, ventilator with a power of the order of 2000 kw and separator with a power of the order of 200 kw. The specific electrical energy consumed can be calculated by the following relation:

$$CEES = \frac{P_m + P_v + P_s + P_a}{Q_m} \quad (1)$$

With:

P_m: main engine power (kw).

P_v: ventilator power (kw).

P_s: power of the separator (kw).

P_a: auxiliary power (kw).

Q_m: mass flow rate of cement (t/h).

III. RESULTS AND DISCUSSIONS

In this study, the effect of feed rate (x_1), air flow (x_2) and separator speed (x_3) on the specific electrical energy (CEES) of the cement crusher has been studied. The feed rate of raw material varies between 160 t/h and 300 t/h. For our study and in order to keep the crusher stable, whatever the conditions, two values for the flow have been chosen: 240 t/h and 250 t/h. For the air flow, two values have been selected for the study: 680000 m^3/h and 720000 m^3/h. For the separator speed we have chosen to slightly vary this parameter around its running value which is 89 tr / min. We retain 88 and 90 rpm. The table 2 shows the levels of the selected parameters and their assigned values.

The studied variable is the CEES of the crusher (principal response, y). In order to get an idea of the influence of the independent variables (x_1, x_2 and x_3) on the quality of the cement, we have also chosen the fineness as the second output (see Figure 2).

Table 2: The experimental ranges and levels of independent variables.

	Feed flow (t/h)	Air flow (m^3/h)	Separator speed (tr/min)
Symbol / Level	X_1	X_2	X_3
-1	260	680000	88
+1	276	720000	90

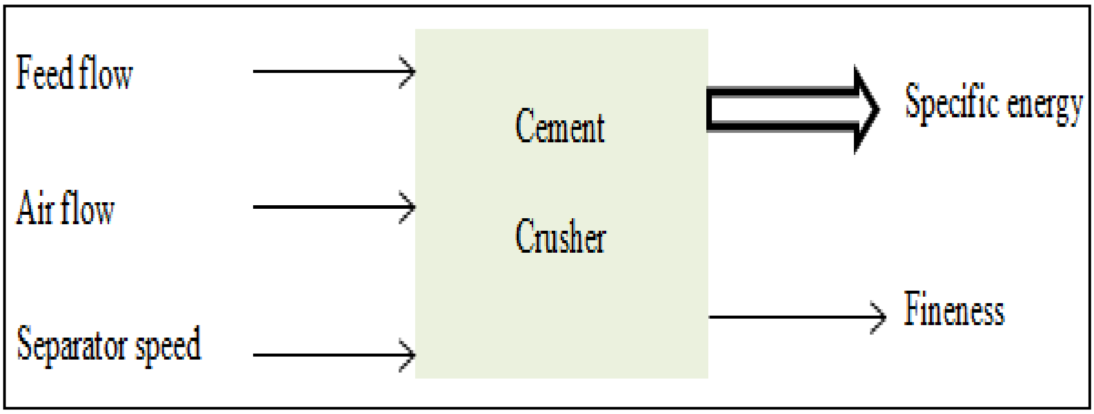

Figure 2: Simplified schema of studied system.

In reality, the parameters rarely act independently of each other. The influence of a parameter on the response may depend on the level of the other parameters. For that, in this study, the experimental design method has been employed, which consists of a powerful method to study the influence of factors or parameters and their interactions on a response of a given system [14-16]. In this study a full factorial design 2^3 was adopted to model CEES as a function of feed rate (x_1), air flow (x_2)and separator speed (x_3). The test matrix corresponding to this design is shown in Table 3 [17]. The behavior of the system can be explained by the following model [18, 19]:

$$Y = q_0 + q_1x_1 + q_2x_2 + q_3x_3 + q_{12}x_1x_2 + q_{13}x_1x_3 + q_{23}x_2x_3 + q_{123}x_1x_2x_3 \quad (2)$$

Where y is the response (dependent variable), q_i and $q_{ij}$are the linear and interaction terms, respectively [20, 21] and x_i is the coded value of i^{th} variable. The coded values were obtained from the following relationship [22-24]:

$$x_i = \frac{X_i - X_0}{\Delta X_i} \quad (3)$$

With: $X_0 = (X_{imax} + X_{imin})/2$; $\Delta X_i = (X_{imax} - X_{imin})/2$

Where x_i is the coded value of i^{th} variable, X_i is the encoded value of i^{th} variable, $X_0$is the value of X_i at the center point of the investigation domain and ΔX_i is the step size. Here, X_{imax} and X_{imin} represent the maximum and the minimum level of factor i in natural unit, respectively.

Table 3: Experimental design matrix.

	I	x_1	x_2	x_3	x_1x_2	x_1x_3	x_2x_3	$x_1x_2x_3$	Y
1	+	-	-	-	+	+	+	-	27.26
2	+	+	-	-	-	-	+	+	23.74
3	+	-	+	-	-	+	-	+	28.31
4	+	+	+	-	+	-	-	-	27.36
5	+	-	-	+	+	-	-	+	27.64
6	+	+	-	+	-	+	-	-	25.73
7	+	-	+	+	-	-	+	-	33.82
8	+	+	+	+	+	+	+	+	27.75
coefficients	27.7	-1.56	1.61	1.03	-0.2	-0.43	0.44	-0.84	
low level	-	260	680000	88					
medium level	-	268	700000	89					
high level	-	276	720000	90					

The composition of the cement used in this study is given in Table 4. During each test, the following constraints have been respected:

- ✓ the same quality of the clinker;
- ✓ the same quality of cement produced;
- ✓ a grinding time of 1h.

Table 4: Composition of the cement used in this study (CPJ 45).

% Clinker	% Limestone	% Gypsum	% Fly ash
60	26	6	8

In order to ensure the clinker quality, it was necessary to take a sample of the clinker that will be introduced into the crusher before the start of each test. Indeed, at the entrance of the crusher, a sample of one m^2 of clinker has been taken, which corresponds to a mass of 25 kg. To obtain the particle size distribution of the sample, a vibration sieving apparatus has been used. Figure 3 shows the percentage of particles that passed through sieves of different apertures.

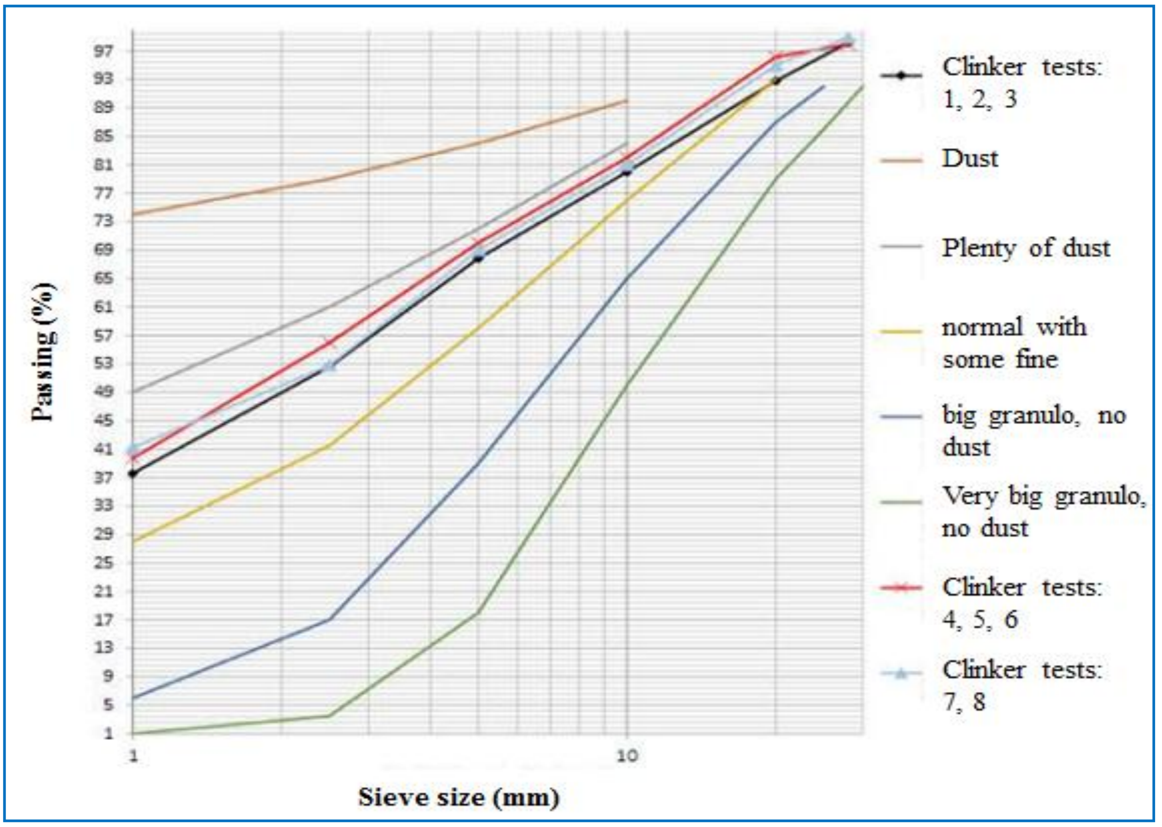

Figure 3: Particle size distribution of test clinker.

The curves of the clinker used for the different tests have been compared with the reference curves. The results show that the clinker curves lie between two reference curves: that of normal clinker with some fines and that of clinker with plenty of dust. The presence of particles larger than 10 mm allows us to deduce that for all the tests we used a normal clinker with some fines.

In order to ensure the clinker fineness, the samples of cement have been taken each 10 minutes for one hour and this during each test. Then, 10 grams of the sample to be analyzed has been passed through a sieve of 45µm for 2 minutes and finally the refusal mass have been weighed. The fineness has been calculated according to the following formula:

$$Fineness = refusal\,rate\,(\%) = \frac{m_2}{m_1} \times 100 \quad (4)$$

Where m_1 is the initial weight and m_2 is the weight after sieving. Table 5 summarizes the results obtained for each test concerning the clinker fineness. The results show that the quality aspect is well respected by the tests carried out.

Table 5: Fineness results.

	Fineness (45µm) %							
Samples	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7	Test 8
1	4.72	4.81	4.81	4.45	4.02	3.2	2.43	3.8
2	4.25	4.92	5.46	4.15	4.52	3.04	2.51	3.87
3	4.29	5.20	4.86	4.02	4.31	2.81	2.78	3.99
4	4.42	5.16	5.79	4.54	4.21	2.77	2.94	4.11
5	4.31	5.35	4.98	4	4.63	2.62	2.83	3.67
6	4.22	5.12	4.94	4.64	4.54	2.25	2.72	4.06
Average	4.37	5.09	5.14	4.3	4.37	2.82	2.7	3.91

Figure 4 shows that the tests whose fineness comes out of the interval required by the cement plant (4 ± 0.5%) are the tests 2, 3, 6 and 7. We have determined their compressive strengths. The results obtained are shown in Table 6.

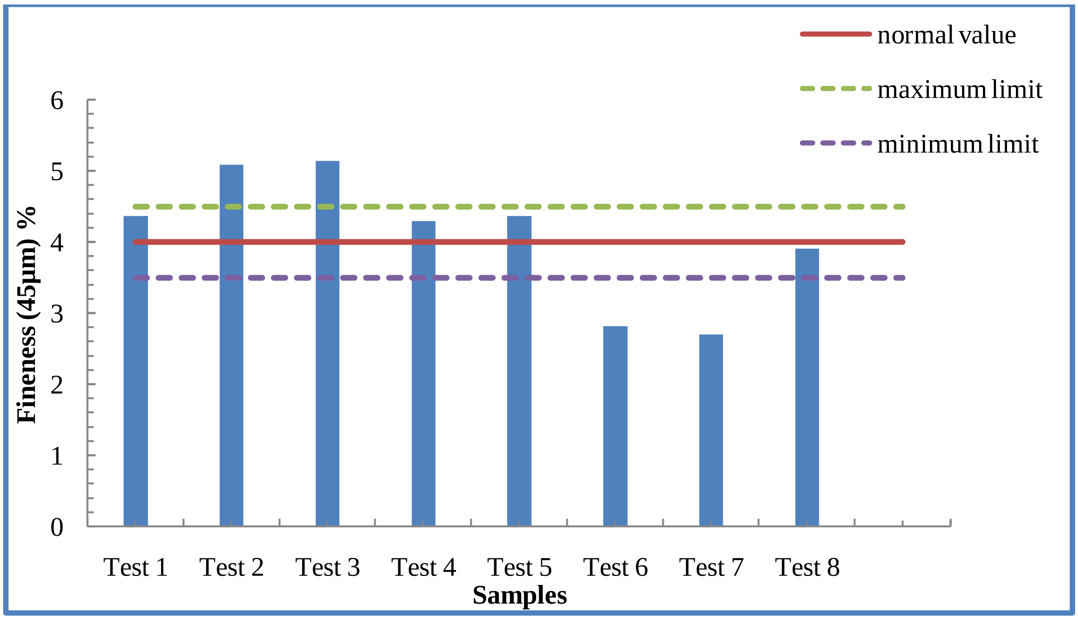

Figure 4: Fineness results.

Table 6: Compressive strengths.

Test number	Compressive strength (2 days, MPa)	Compressive strength (7 days, MPa)
2	13.43	27.17
3	13.2	27.98
6	16.1	30.85
7	16.34	31.42
minimum limit	12.5	25
minimum normal value	15	26
maximum normal value	19	34
maximum limit	20	36

Each coefficient of the model (equation 2) is calculated by taking the sum of the responses, each of them being assigned the sign of the column corresponding to this coefficient, divided by the number of tests [25].

$$q_0 = \frac{Y_1 + Y_2 + Y_3 + Y_4 + Y_5 + Y_6 + Y_7 + Y_8}{8} \quad (5)$$

$$q_1 = \frac{-Y_1 + Y_2 - Y_3 + Y_4 - Y_5 + Y_6 - Y_7 + Y_8}{8} \quad (6)$$

$$q_2 = \frac{-Y_1 - Y_2 + Y_3 + Y_4 - Y_5 - Y_6 + Y_7 + Y_8}{8} \quad (7)$$

$$q_3 = \frac{-Y_1 - Y_2 - Y_3 - Y_4 + Y_5 + Y_6 + Y_7 + Y_8}{8} \quad (8)$$

$$q_{12} = \frac{Y_1 - Y_2 - Y_3 + Y_4 + Y_5 - Y_6 - Y_7 + Y_8}{8} \quad (9)$$

$$q_{13} = \frac{Y_1 - Y_2 + Y_3 - Y_4 - Y_5 + Y_6 - Y_7 + Y_8}{8} \quad (10)$$

$$q_{23} = \frac{Y_1 + Y_2 - Y_3 - Y_4 - Y_5 - Y_6 + Y_7 + Y_8}{8} \quad (11)$$

$$q_{123} = \frac{-Y_1 + Y_2 + Y_3 - Y_4 + Y_5 - Y_6 - Y_7 + Y_8}{8} \quad (12)$$

The mathematical model is written thus:

$$Y = 27.7 - 1.56x_1 + 1.61x_2 + 1.03x_3 - 0.2x_1x_2 - 0.43x_1x_3 + 0.44x_2x_3 - 0.84x_1x_2x_3 \quad (13)$$

The results show that the increase in the feed rate causes a decrease in the CEES, while an increase in the air flow or separator speed causes a CEES increase. To validate the model, we tested it using the domain center of each factor: x_1=245 (t/h) ; x_2=700000 (m^3/h) ; x_3=89 (tr/min). Table 7 represents the results obtained. As Table 6 shows, the empirical model found gives results closer to reality. So we can conclude that the mathematical model provided a satisfactory fit to the experimental data.

Table 7: Model validation results.

	Calculated	realized	absolute error	relative error %
Specific electrical energy	26.14	26.8	1.08	2.52

The figures below illustrate the effects of each factor on the CEES:

- Feed rate effect

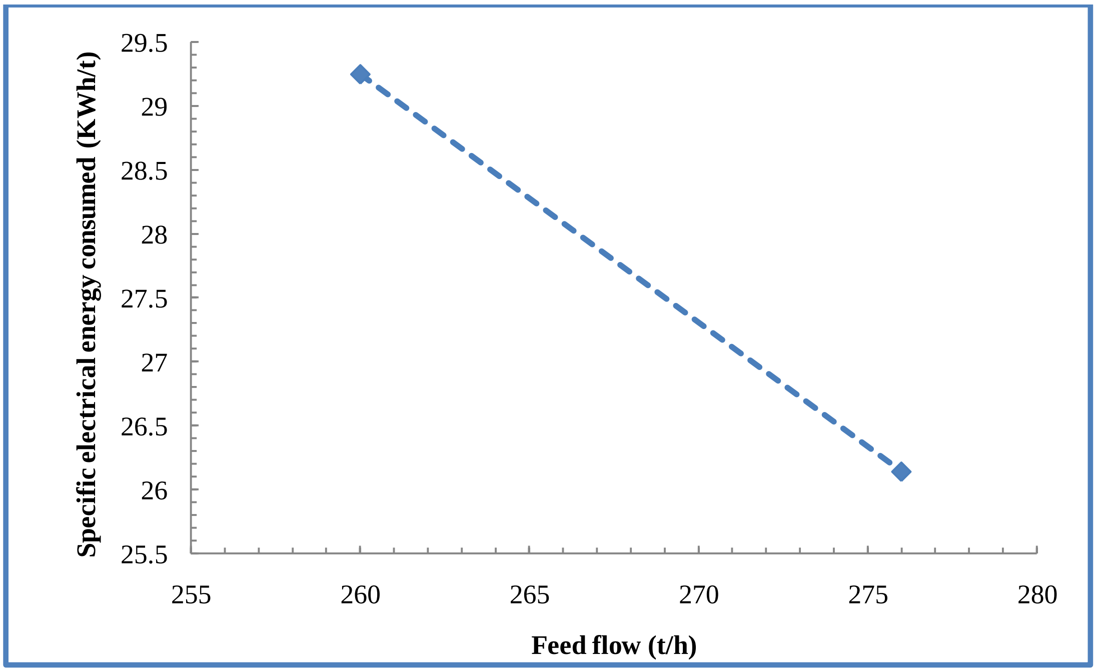

Figure 5: Feed rate effect.

Therefore, an increase in the feed rate results in a decrease in the specific electrical energy consumed of crusher.

- Airflow effect

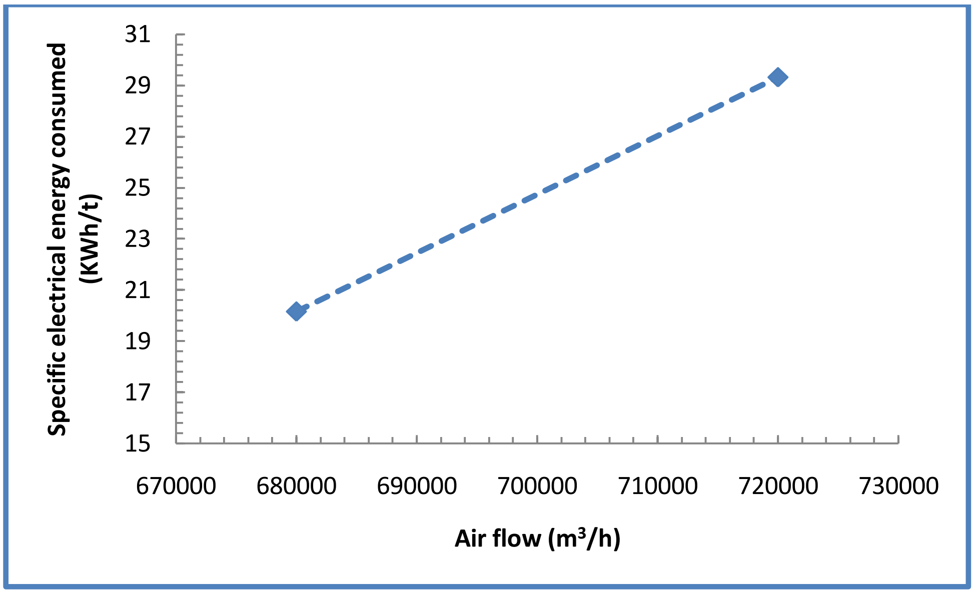

Figure 6: Air flow effect.

So when we increase the air flow, the specific electrical energy consumed increases.

- Separator speed effect

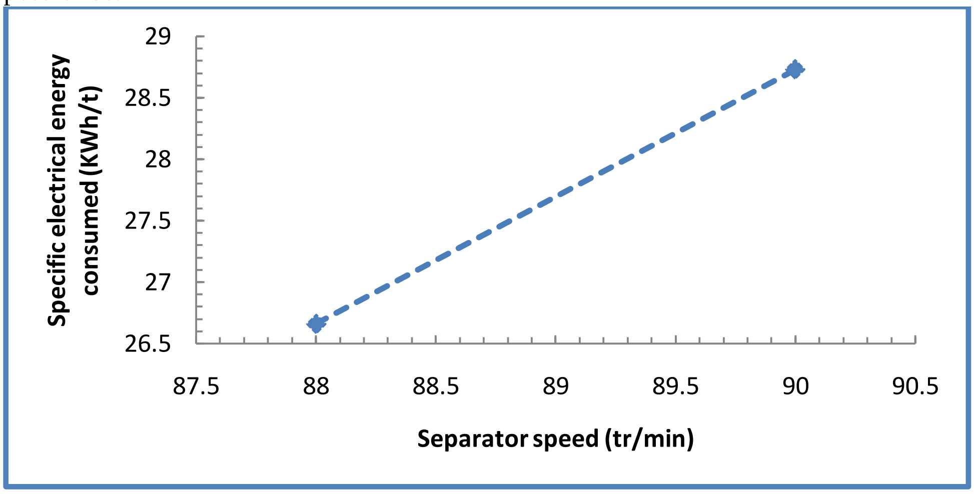

Figure 7: Separator speed effect.

Therefore, an increase in the separator speed results in an increase of the specific energy.

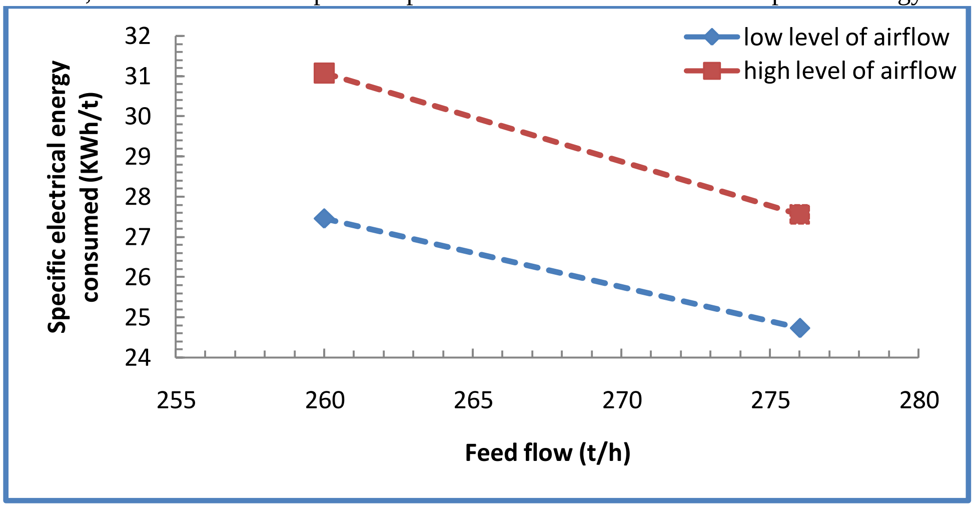

Figure 8: Effect of the interactions between the feed flow and air flow.

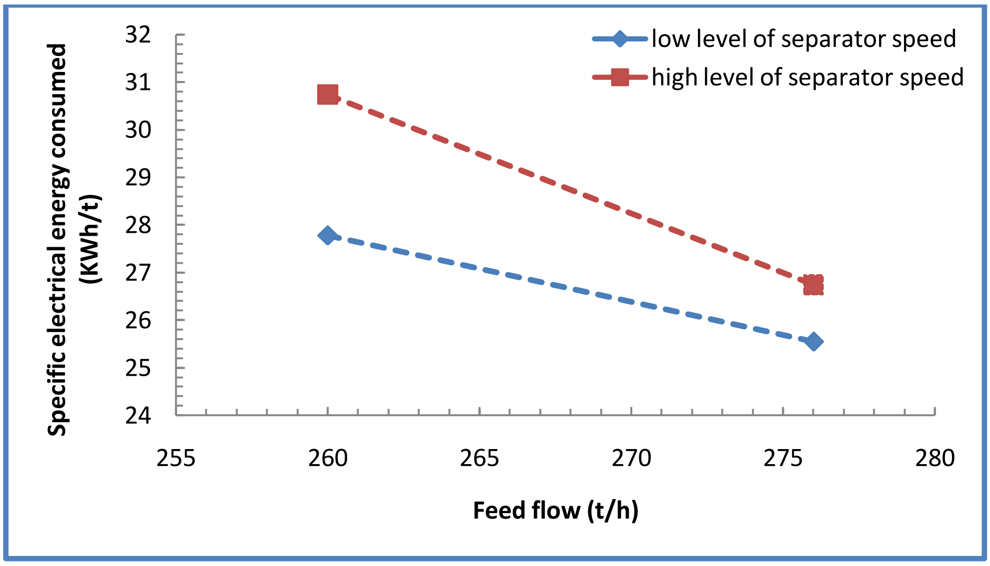

Figure 9: Effect of the interactions between the feed flow and separator speed.

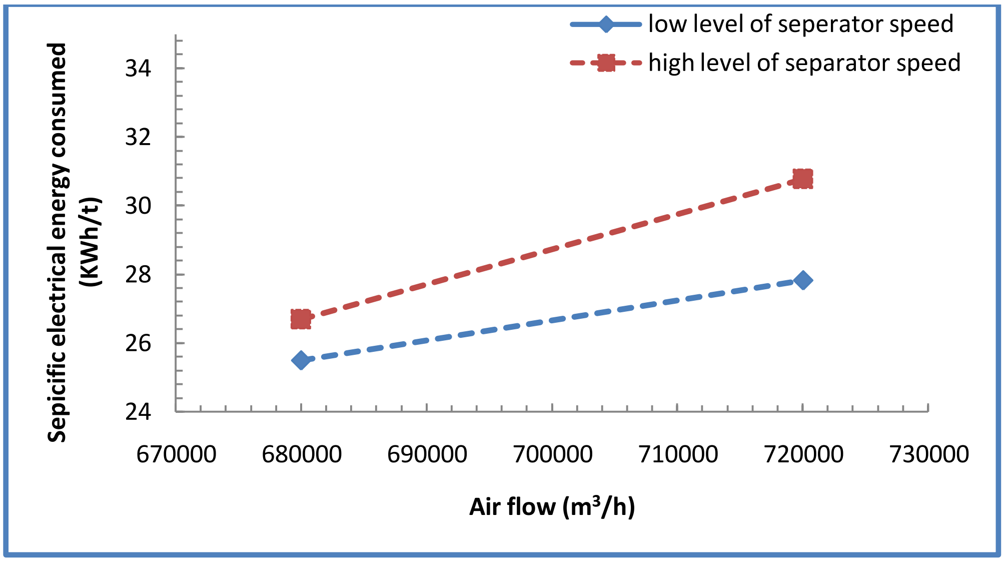

Figure 10: Effect of the interactions between the air flow and separator speed.

From Figures 8, 9 and 10 all the interactions have a negligible effect on the specific energy.

In order to determine the values of feed rate (X_1), air flow (X_2) and separator speed (X_3) giving a minimum electrical consumption, the coded model (equation 13) has been transferred to the encoded model based on the equation 3. The optimization problem is given below.

$$\begin{cases} \boldsymbol{Min}\ Y = 27.7 - 1.56\frac{X_1 - X_{10}}{\Delta X_1} + 1.61\frac{X_2 - X_{20}}{\Delta X_2} + 1.03\frac{X_3 - X_{30}}{\Delta X_3} - 0.2\frac{X_1 - X_{10}}{\Delta X_1}\frac{X_2 - X_{20}}{\Delta X_2} - 0.43\frac{X_1 - X_{10}}{\Delta X_1}\frac{X_3 - X_{30}}{\Delta X_3} + 0.44\frac{X_2 - X_{20}}{\Delta X_2}\frac{X_3 - X_{30}}{\Delta X_3} \\ 260 \leq X_1 \leq 276 \\ 680000 \leq X_2 \leq 720000 \\ 88 \leq X_3 \leq 90 \end{cases}$$

This problem has been solved using the excel solver (simplex method). The optimization results are given in Table 8. As shown in Table 8, to have minimum electrical power consumption it is necessary to set the feed rate to 276 t/h, air flow to 680000 m^3/h and separator speed to 88 tr/min.

Table 8: Optimization results.

Feed flow (t/h)	Air flow (m^3/h)	Separator speed (tr/min)	$CEES_{min}$
276	680000	88	21.94 kwh/t

IV. CONCLUSION

The specific electrical energy (CEES) of the cement crusher has been modeled and optimized as function of feed rate, air flow and separator speed applying full factorial design. The proposal model provided a satisfactory fit to the experimental data. The results obtained show that the increase in the feed rate results in a decrease in the specific electrical energy, while the increase in the air flow and the separator speed causes a specific electrical energy increase. The results also show that all the interactions have a negligible effect on the specific energy. According the optimization results, to have minimum electrical power consumption it is necessary to set the feed rate to 276 t/h, air flow to 680000 m^3/h and separator speed to 88 tr/min.

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