Simulation model for the calcination process of cement.

Idalia Flores[a]Guillermo Perea[b]
(a) Facultad de Ingeniería, UNAM
(b) Facultad de Ingeniería, UNAM
[a] idalia@unam.mx, [b]guillermo.perea@live.com.mx

Abstract

Simulation is an important tool when a phenomenon or input-output relationships of a system makes its operation or testing impossible, expensive, dangerous or impractical. This paper develops a simulation model for the burning process of Portland cement. The methodology used is the one used in simulation, which establishes the definition of the problem, analysis of the variables to be modeled, executes a basic model, a detailed model development, validation, reports and conclusions.

Keywords: *Simulation, calcinations, clinker, Cruz Azul cement, Arena, Simio.*

1. Introduction

Cement is one of the main inputs in the construction industry in Mexico; domestic production was 42 million tons in 2010. The calcinations of cement unit is a system consisting of a Preheater, Kiln and Cooler (PHE), which raises the temperature of the limestone powder to 1.450° C, causing physicochemical changes and the formation of silicates in a granular mixture called clinker. Simulating the system PHE will allow us to analyze the formation of clinker through a mass-energy balance.

To optimize this process we require a model that allows us to manipulate the different variables of the system. The aim of this paper is to build a simulation model of the calcination process in cement production, assessing the behavior of the input, distribution of the process, and output variables.

Figure 1 shows some components of the cement.


Figure 1 Cement components

2. Manufacturing process.

2.1 Obtaining raw materials.

The cement manufacturing process begins with the extraction of raw materials that are found in deposits, usually in open quarries. The quarries are operated by controlled blasting in the case of hard materials such as limestone and slates, while excavators are used to dig out the soft materials (clays). Once the material is extracted and classified, it is then crushed to a particle size suitable for the mill product and is transported by conveyer belt or truck to the factory for storage in the prehomogenization pile.

2.2 Homogenization and grinding of raw.

In the prehomogenization pile, the crushed material is stored in top layers to be selected later in a controlled manner. The blending bed can prepare the proper dosage of components by reducing variability.

Subsequently, these materials are ground in ball or vertical mills to make them smaller and thus make it easier to fire them in the kiln. In the vertical mill, the material is crushed by the pressure of its roller on a turntable. From there, the raw material (powder or rawmix) is stored in a silo to increase the uniformity of the mixture.

2.3 Preheater, kiln and cooler (PHE).

The kiln is powered by means of the cyclone preheater that heats the feedstock to facilitate firing. Ground material or rawmix is inserted through the top of the tower and drops through it. Meanwhile, the gases from the kiln, which are at a high temperature, rise against the current, thus the rawmix is preheated before entering the kiln.

As the rawmix progresses in the kiln while it rotates, the temperature increases to reach 1.500 ° C. At this temperature complex chemical reactions occur that result in the clinker.

To achieve the temperatures required for firing the raw materials and the production of clinker, the kiln has a main flame that burns at 2, 000 º C. In some cases there is also a secondary flame located in the combustion chamber in the preheater tower.

Once the clinker leaves the kiln, a cooler is introduced in inject cold air to lower the temperature from 1.400 ° C to 100 º C. The hot air generated in this device is returned to the kiln to support combustion, thereby improving the energy efficiency of the process.

2.4 Grinding of the clinker.

Once the clinker is obtained, it is mixed in a cement mill with gypsum and additives, in the right proportions. Inside, the materials are ground, mixed and homogenized.

The mills can consist of (horizontal and vertical) rollers or balls. The later consists of a large rotating tube with steel balls inside. Thanks to the rotation of the mill, the balls collide, crushing the clinker and additives to a fine homogeneous rawmix: **cement**.

2.5 Distribution.

Finally, the cement is stored in silos, separated according to its various classes before being bagged or loaded onto a truck for transport by road or rail.

3. The simulation model for the cement.

3.1. Calcination process analysis.

The reactions that occur in the calcination process are:

- Evaporation of water from the mixture.
- Elimination of combined water in the clay.
- Dissociation of magnesium carbonate.
- Dissociation of calcium carbonate.
- Reaction in the kiln, mixing the lime and clay.

The kiln (heat exchanger-cooler) is the equipment that determines the production, being the most important part of the process.

The clinker is produced by heating the properly dosed rawmix at high temperatures in an oxidizing atmosphere generally. The reactions of clinker produced essentially four main elements: CaO, SiO_2, Al_2O_3, Fe_2O_3 to form silicates with hydraulic properties. In overall, the clinker formation process can be divided into four parts:

Temperature (ºC)	Reactions
20-100	$CaCO_3.MgCO_3.Al_2O_3.SiO_2.Fe_2O_3.H_2O$ » $CaCO_3.MgCO_3.Al_2O_3.SiO_2.Fe_2O_3 + H_2O_{(V)}$ Dehydration of the mixture(evaporation of free water)
100-400	$Al_2O_3.2SiO_2.H_2O$ » $Al_2O_3 + SiO_2 + 2H_2O$ $_{(v)}$ It expels water of crystallization (water removal combined with clay)
400-900	Chemical water is released.

Table 1 Drying

Temperature (ºC)	Reactions
500-900	$CaCO_3$ » $CaO + CO_2$ Decarbonation $MgCO_3$ » $Mg + CO_2$ Dissociation of magnesium carbonate CO_2 is expelled
Debajo de 800	$CaO + Al_2O_3$ » $CaO.Al_2O_3$ Formation of calcium aluminate $CaO + Fe_2O_3$ » $CaO.Fe_2O_3$ Formation of ferrous oxide
800-900	$CaO + SiO_2$ » $CaO.SiO_2$ Formation of calcium silicate
900-950	$5CaO + 3Al_2O_3$ » $5CaO.3Al_2O_3$ Formation of calcium trialuminato
950-1200	$2CaO + SiO_2$ » $2CaO.SiO_2$ Formation of dicalcium silicate (C2S)

Table 2 Calcination

Temperature (ºC)	Reactions
1200-1300	$3CaO + Al_2O_3$ » $3CaO.Al_2O_3$ Formation of tricalcium aluminate (C3A)
1260	$4CaO + Al_2O_3 + Fe_2O_3$ » $4CaO.Al_2O_3.Fe_2O_3$ Formation of Tetracalcium ferroaluminato
1260-1450	$3CaO + SiO_2$ » $3CaO.SiO_2$ Formation of tricalcium silicate (C3S) from C2S and free lime $CaO + 2CaO.SiO_2$ » $3CaO.SiO_2$

Table 3 Sintering and clinker

Temperature (ºC)	Reactions
1450	Belita Formation of and Alita
1300-1240	Crystallization of aluminates and ferrites

Table 4 Cooled

3.2 System mass balance-preheater kiln-cooler (PHE).

PHE Process is developed in the following steps:

3.2.1. Precalcination of the raw mixture. The preheater has a preheater, which heats the raw mixture of 60-70 ° C to 800-850 ° C, usually fueled by natural gas as fuel and use the waste gases from the kiln.

3.2.2. Formation of clinker.

The formation of the clinker takes place in the rotary kiln, which is fed with the raw mixture from the preheater and, in turn, introduces hot air (secondary) cooler.

3.2.3. Cooling of clinker.

The cooler consists of fans with variable flow through variable speed drives.

3.2.4 Cooling gases.

The waste gases are cooled in a cooling tower, which is constituted by a system of nozzles and decanting to separate the oil carried by the gases. However, decanting is not enough, so an electrostatic filter is also used.

3.2.5. Separation of dust from waste gases.

An electrostatic precipitator, consisting of plate-rapping systems and electric fields, is used to separate or precipitate dust from raw waste gases.

3.2.6. Separation of dust from the cooler.

It uses an electrostatic filter that separates the particles of dust from clinker cooler air

Mass balance:

The aforementioned integrated process is summarized in the following block diagram:

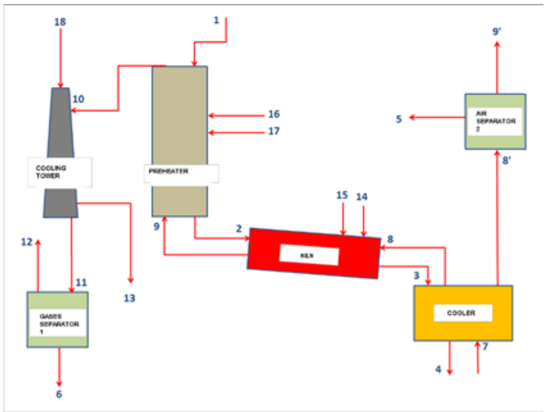
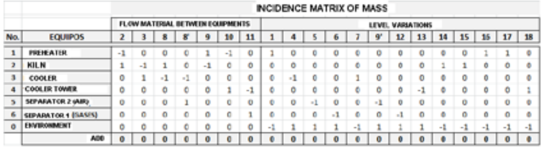


Figure 2 Mass balance

To calculate the mass flow rates, the incidence matrix for mass was developed, according to the mass flows that get in and out of the equipment:



INCIDENCE MATRIX OF MASS

		FLOW MATERIAL BETWEEN EQUIPMENTS							LEVEL VARIATIONS												
No.	EQUIPOS	2	3	8	8'	9	10	11	1	4	5	6	7	9'	12	13	14	15	16	17	18
1	PREHEATER	-1	0	0	0	1	-1	0	1	0	0	0	0	0	0	0	0	0	1	1	0
2	KILN	1	-1	1	0	-1	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0
3	COOLER	0	1	-1	-1	0	0	0	0	-1	0	0	1	0	0	0	0	0	0	0	0
4	COOLER TOWER	0	0	0	0	0	1	-1	0	0	0	0	0	0	0	-1	0	0	0	0	1
5	SEPARATOR 2 (AIR)	0	0	0	1	0	0	0	0	0	-1	0	0	-1	0	0	0	0	0	0	0
6	SEPARATOR 1 (GASES)	0	0	0	0	0	0	1	0	0	0	-1	0	0	-1	0	0	0	0	0	0
0	ENVIRONMENT	0	0	0	0	0	0	0	-1	1	1	1	-1	1	1	1	-1	-1	-1	-1	-1
	ADD	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 5 Incidence matrix for mass

3.3 Simulation model for calcination unit No. 9 of Cruz Azul cement plant, Hidalgo, Mexico.

Cooperativa La Cruz Azul S.C., a homegrown company from the Mexican state of Hidalgo, currently ranks third in national cement production after Cemex and Apasco.

Due to the complexity and automation of most processes in the Cooperativa La Cruz Azul SCL, it is somewhat difficult to find areas of opportunity for improvement. At the present time, Cruz Azul has project engineering areas and an optimization department whose job is to constantly search for innovative technologies or technical information that would maximize existing resources, evaluate the replacement of equipment, performance and energy fuels and, if necessary, to supervise the construction of an entirely new factory. Usually these areas (or project optimization) work separately and there is a significant difference between the scope of each of them.

However, in both the Project area and the area of optimization, the firing is the key process in cement manufacturing. From the roasting process is designed the size and capacity of the kiln, which in turn determines the capacity of the preheater building itself and, in consequence, the various skills of the teams that will take part in the design of a production line or a complete plant.

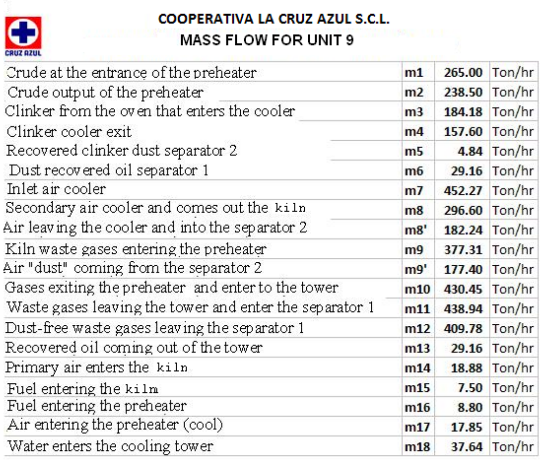
The following questions arise:

- Why not analyze the input-output flows under a controlled environment of mass-energy and time?
- Why not gradually change the way people work in the process engineering department, using a scientific methodology provided by simulation?

The system to be analyzed consists of a combustion process as show below.

3.3.1 Collecting the information.

Solving the system of mass balance equations with real data of the calcination unit No.9, we have:



COOPERATIVA LA CRUZ AZUL S.C.L.
MASS FLOW FOR UNIT 9

Crude at the entrance of the preheater	m1	265.00	Ton/hr
Crude output of the preheater	m2	238.50	Ton/hr
Clinker from the oven that enters the cooler	m3	184.18	Ton/hr
Clinker cooler exit	m4	157.60	Ton/hr
Recovered clinker dust separator 2	m5	4.84	Ton/hr
Dust recovered oil separator 1	m6	29.16	Ton/hr
Inlet air cooler	m7	452.27	Ton/hr
Secondary air cooler and comes out the kiln	m8	296.60	Ton/hr
Air leaving the cooler and into the separator 2	m8'	182.24	Ton/hr
Kiln waste gases entering the preheater	m9	377.31	Ton/hr
Air "dust" coming from the separator 2	m9'	177.40	Ton/hr
Gases exiting the preheater and enter to the tower	m10	430.45	Ton/hr
Waste gases leaving the tower and enter the separator 1	m11	438.94	Ton/hr
Dust-free waste gases leaving the separator 1	m12	409.78	Ton/hr
Recovered oil coming out of the tower	m13	29.16	Ton/hr
Primary air enters the kiln	m14	18.88	Ton/hr
Fuel entering the kilm	m15	7.50	Ton/hr
Fuel entering the preheater	m16	8.80	Ton/hr
Air entering the preheater (cool)	m17	17.85	Ton/hr
Water enters the cooling tower	m18	37.64	Ton/hr

Table 6 Mass flow of calcination unit 9

3.3.2 Basic model.

The basic model was developed in Arena, which is an initial flowchart where the flow of rawmix fed into the Preheater-Kiln-Cooler system (PHE), and the chaotic movement is undergoes in the cyclone preheater (allocation probability) determines, in a linear fashion, both the consumption of fuel and electrical power.

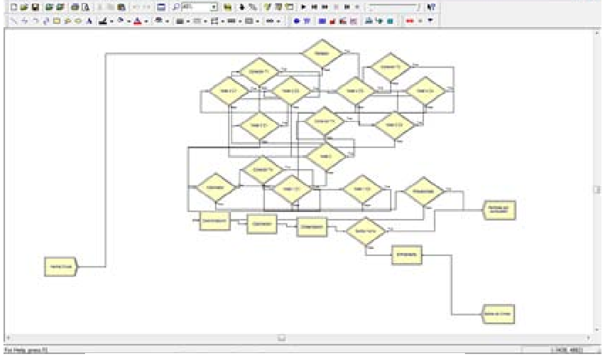


Figure 3 Flow chart for the PHE

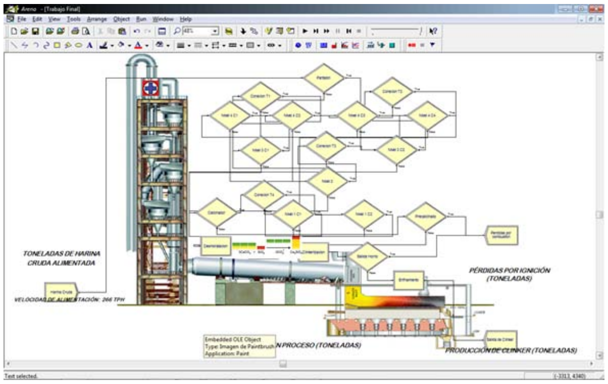


Figure 4 Basic model with Arena

3.3.3. Complete Model.

From the calculated mass balance, we developed a new model from the inputs and outputs, by considering mass and the stoichiometric analysis of the raw materials and the heat capacity of the fuel. APE software was used.

3.3.4 Flowcharts

According to the block diagram in which inputs and outputs represent the mass, we proceeded to develop flow charts for the calcination process.

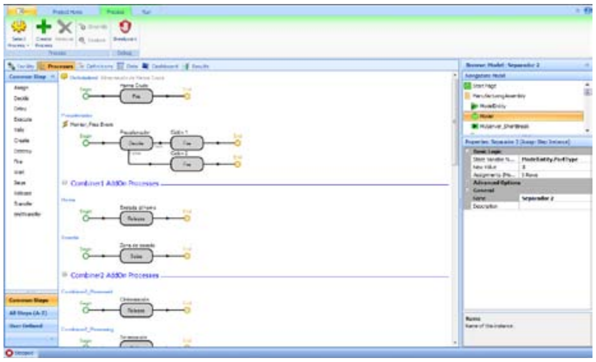


Figure 5 Flowchart for the calcination process

3.3.5 Display

We subsequently assigned the variables representing the masses (m_1, m_2, m_3...) to form the input-output system mass. The arrival of a continuous entity called rawmix is determined to simulate a power of 265 Ton / hr within the system.

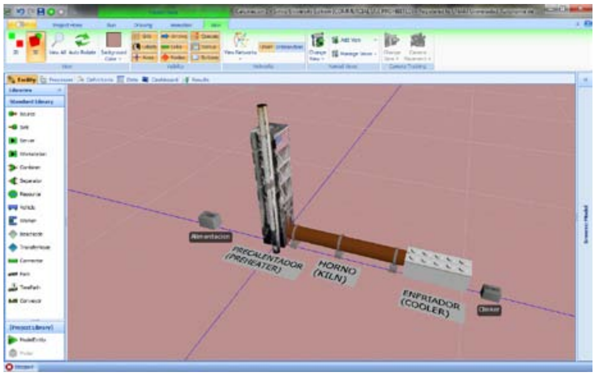


Figure 6 Simulations with SIMIO

We observe in the Arena model that there is a chaotic movement of rawmix particles in the cyclone, so that we determine that they are probability fluxes (approximately 65% -35%). The temperature is monitored at the inlet to the Preheater, and at the inlet , center and outlet from the kiln, at the inlet and outlet of the clinker cooler. Fuel consumption is based on the flow of rawmix, which has already been decarbonated in order to achieve more efficient calcination. It simulates the consumption of coke (petroleum), whose consumption is approximately 7.500 kg / hr in the preheater (preheating) and 8.800 kg / hr in the main burner (kiln). The flow in the supply of rawmix is between 64.7 - 65 Ton / hr, so we used the linear function L (64.7-65) to simulate the behavior.

3.3.6 Experiments

In order to have more results, 10 experiments were performed, as shown below:

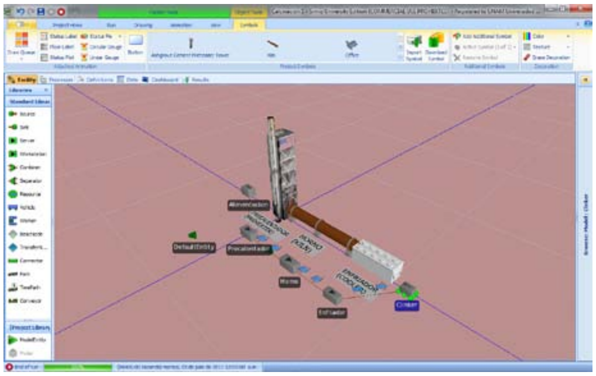
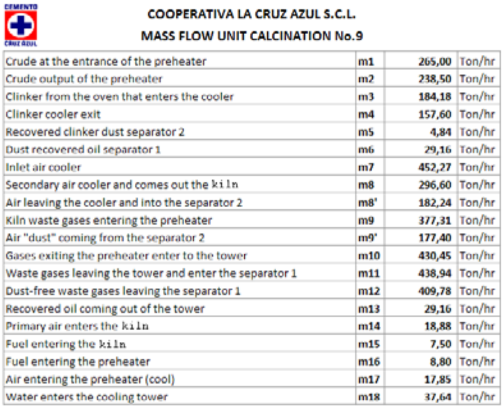


Figure 7 Simulation experiments

As a result, we obtained the following data:



COOPERATIVA LA CRUZ AZUL S.C.L.
MASS FLOW UNIT CALCINATION No.9

Crude at the entrance of the preheater	m1	265,00	Ton/hr
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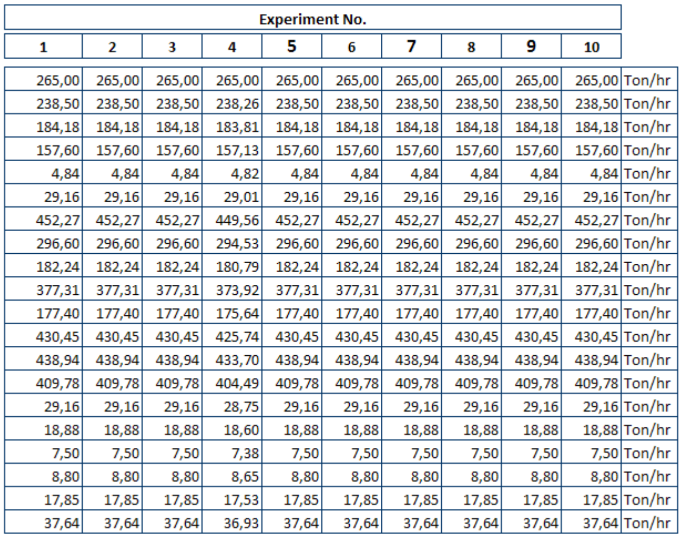
Dust-free waste gases leaving the separator 1	m12	409,78	Ton/hr
Recovered oil coming out of the tower	m13	29,16	Ton/hr
Primary air enters the kiln	m14	18,88	Ton/hr
Fuel entering the kiln	m15	7,50	Ton/hr
Fuel entering the preheater	m16	8,80	Ton/hr
Air entering the preheater (cool)	m17	17,85	Ton/hr
Water enters the cooling tower	m18	37,64	Ton/hr

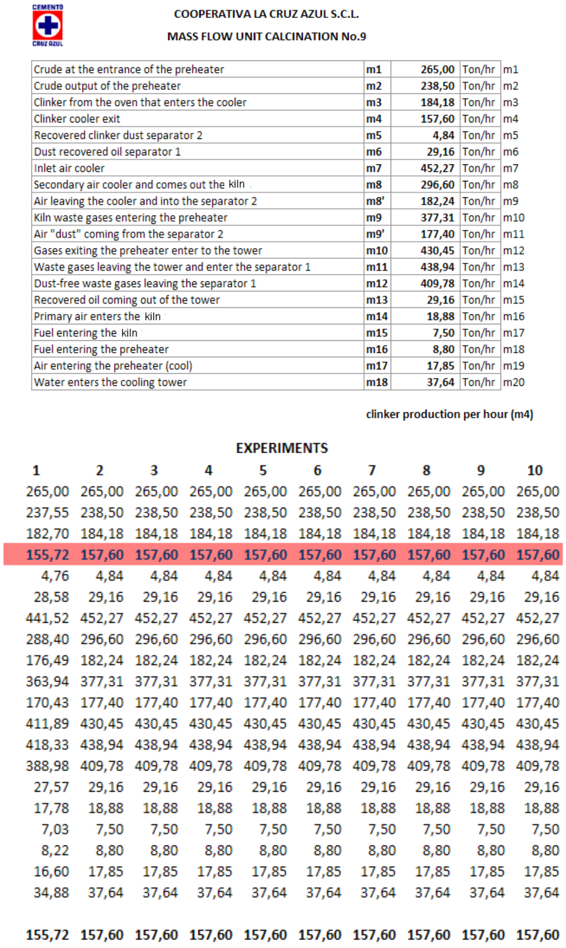


Experiment No.										
1	2	3	4	5	6	7	8	9	10	
265,00	265,00	265,00	265,00	265,00	265,00	265,00	265,00	265,00	265,00	Ton/hr
238,50	238,50	238,50	238,26	238,50	238,50	238,50	238,50	238,50	238,50	Ton/hr
184,18	184,18	184,18	183,81	184,18	184,18	184,18	184,18	184,18	184,18	Ton/hr
157,60	157,60	157,60	157,13	157,60	157,60	157,60	157,60	157,60	157,60	Ton/hr
4,84	4,84	4,84	4,82	4,84	4,84	4,84	4,84	4,84	4,84	Ton/hr
29,16	29,16	29,16	29,01	29,16	29,16	29,16	29,16	29,16	29,16	Ton/hr
452,27	452,27	452,27	449,56	452,27	452,27	452,27	452,27	452,27	452,27	Ton/hr
296,60	296,60	296,60	294,53	296,60	296,60	296,60	296,60	296,60	296,60	Ton/hr
182,24	182,24	182,24	180,79	182,24	182,24	182,24	182,24	182,24	182,24	Ton/hr
377,31	377,31	377,31	373,92	377,31	377,31	377,31	377,31	377,31	377,31	Ton/hr
177,40	177,40	177,40	175,64	177,40	177,40	177,40	177,40	177,40	177,40	Ton/hr
430,45	430,45	430,45	425,74	430,45	430,45	430,45	430,45	430,45	430,45	Ton/hr
438,94	438,94	438,94	433,70	438,94	438,94	438,94	438,94	438,94	438,94	Ton/hr
409,78	409,78	409,78	404,49	409,78	409,78	409,78	409,78	409,78	409,78	Ton/hr
29,16	29,16	29,16	28,75	29,16	29,16	29,16	29,16	29,16	29,16	Ton/hr
18,88	18,88	18,88	18,60	18,88	18,88	18,88	18,88	18,88	18,88	Ton/hr
7,50	7,50	7,50	7,38	7,50	7,50	7,50	7,50	7,50	7,50	Ton/hr
8,80	8,80	8,80	8,65	8,80	8,80	8,80	8,80	8,80	8,80	Ton/hr
17,85	17,85	17,85	17,53	17,85	17,85	17,85	17,85	17,85	17,85	Ton/hr
37,64	37,64	37,64	36,93	37,64	37,64	37,64	37,64	37,64	37,64	Ton/hr

Table 7 Simulation experiments

3.3.7 Model Validation

In order to validate the model, we consider the nominal production of the calcination unit No.9 Cruz Azul, according to the information provided by the area of new projects, nominal output is 157.65 tons / hr of clinker. Considering this fact, along with the 10 experiments and the linear nature of a controlled process, we can validate the statistical behavior of the production of clinker simulated by using the Student t test as shown in the following table:



COOPERATIVA LA CRUZ AZUL S.C.L.

MASS FLOW UNIT CALCINATION No.9

Crude at the entrance of the preheater	**m1**	**265,00**	Ton/hr	m1
Crude output of the preheater	**m2**	**238,50**	Ton/hr	m2
Clinker from the oven that enters the cooler	**m3**	**184,18**	Ton/hr	m3
Clinker cooler exit	**m4**	**157,60**	Ton/hr	m4
Recovered clinker dust separator 2	**m5**	**4,84**	Ton/hr	m5
Dust recovered oil separator 1	**m6**	**29,16**	Ton/hr	m6
Inlet air cooler	**m7**	**452,27**	Ton/hr	m7
Secondary air cooler and comes out the kiln	**m8**	**296,60**	Ton/hr	m8
Air leaving the cooler and into the separator 2	**m8'**	**182,24**	Ton/hr	m9
Kiln waste gases entering the preheater	**m9**	**377,31**	Ton/hr	m10
Air "dust" coming from the separator 2	**m9'**	**177,40**	Ton/hr	m11
Gases exiting the preheater enter to the tower	**m10**	**430,45**	Ton/hr	m12
Waste gases leaving the tower and enter the separator 1	**m11**	**438,94**	Ton/hr	m13
Dust-free waste gases leaving the separator 1	**m12**	**409,78**	Ton/hr	m14
Recovered oil coming out of the tower	**m13**	**29,16**	Ton/hr	m15
Primary air enters the kiln	**m14**	**18,88**	Ton/hr	m16
Fuel entering the kiln	**m15**	**7,50**	Ton/hr	m17
Fuel entering the preheater	**m16**	**8,80**	Ton/hr	m18
Air entering the preheater (cool)	**m17**	**17,85**	Ton/hr	m19
Water enters the cooling tower	**m18**	**37,64**	Ton/hr	m20

clinker production per hour (m4)

EXPERIMENTS

1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
265,00	265,00	265,00	265,00	265,00	265,00	265,00	265,00	265,00	265,00
237,55	238,50	238,50	238,50	238,50	238,50	238,50	238,50	238,50	238,50
182,70	184,18	184,18	184,18	184,18	184,18	184,18	184,18	184,18	184,18
155,72	**157,60**	**157,60**	**157,60**	**157,60**	**157,60**	**157,60**	**157,60**	**157,60**	**157,60**
4,76	4,84	4,84	4,84	4,84	4,84	4,84	4,84	4,84	4,84
28,58	29,16	29,16	29,16	29,16	29,16	29,16	29,16	29,16	29,16
441,52	452,27	452,27	452,27	452,27	452,27	452,27	452,27	452,27	452,27
288,40	296,60	296,60	296,60	296,60	296,60	296,60	296,60	296,60	296,60
176,49	182,24	182,24	182,24	182,24	182,24	182,24	182,24	182,24	182,24
363,94	377,31	377,31	377,31	377,31	377,31	377,31	377,31	377,31	377,31
170,43	177,40	177,40	177,40	177,40	177,40	177,40	177,40	177,40	177,40
411,89	430,45	430,45	430,45	430,45	430,45	430,45	430,45	430,45	430,45
418,33	438,94	438,94	438,94	438,94	438,94	438,94	438,94	438,94	438,94
388,98	409,78	409,78	409,78	409,78	409,78	409,78	409,78	409,78	409,78
27,57	29,16	29,16	29,16	29,16	29,16	29,16	29,16	29,16	29,16
17,78	18,88	18,88	18,88	18,88	18,88	18,88	18,88	18,88	18,88
7,03	7,50	7,50	7,50	7,50	7,50	7,50	7,50	7,50	7,50
8,22	8,80	8,80	8,80	8,80	8,80	8,80	8,80	8,80	8,80
16,60	17,85	17,85	17,85	17,85	17,85	17,85	17,85	17,85	17,85
34,88	37,64	37,64	37,64	37,64	37,64	37,64	37,64	37,64	37,64
155,72	**157,60**	**157,60**	**157,60**	**157,60**	**157,60**	**157,60**	**157,60**	**157,60**	**157,60**

1,6815

H0: $\mu = 158$ Ton/hr

H1: $\mu <> 158$ Ton/hr

Using the t-test, the mean and the standard deviation is calculated with a sample of the 10 experiments:

μ= 157.41

σ= 0.596

n= 10

4. Conclusions

The linearity of an industrial process such as cement calcination represents very slight changes in control variables, because of the importance and criticality of this operation on the final quality of the cement. It has been demonstrated to simulate a controlled continuous production process (24 hours a day 360 days a year) finally yields results that are very close to reality, regardless of the number of variables involved. The simulation that we developed was a process "in constant motion".

There are several international companies that develop the engineering and construction for cement plants, using very complex mass and energy balances to determine the specific capacity of each piece of equipment to be installed, though, of course, the heart of the system is the installed kiln capacity and overall clinker production rate of the calcination unit. Simulation can give different scenarios for the future and allows the company to change or modify important parameters in the production of the cement.

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AUTHORS BIOGRAPHY

Dra. Idalia Flores de la Mota…

Dr. Idalia Flores de la Mota is mathematics at the Faculty of Sciences of the UNAM and studied the Masters and Ph.D. in Operations Research at the Faculty of Engineering of the UNAM. She has published notes, chapters in books, booklets and articles disclosed in international journals. He has been referee of the journals, Simulation, the Journal of Accounting and Administration, Computing Reviews online and Revista Iberoamericana de Automática e Informática Industrial. It belongs to the Institute for Operations Research and the Management Science and is Director of the Center for Simulation McLeod in Mexico.

Ing. Guillermo Perea Rivera.

Industrial engineer, graduated from the National Polytechnic Institute (UPIICSA), currently studying a Masters in Systems Engineering with specialization in Operations Research at the National Autonomous University of Mexico (UNAM). He has worked in the cement industry in the planning and control of projects specifically in Cementos Cruz Azul. Within the concrete industry in the same group has developed databases and applied statistical tools that have increased the efficiency of the information in the technical area He is currently coordinator of new projects.