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Optimization of Heat Consumption in a Rotary Cement Kiln.

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Abstract: - **Optimization study on heat consumption in a rotary cement kiln has been undertaken to make optimum use of heat generated during the pyro process involved in cement clinker production. This research was carried out putting into consideration raw meal quality parameter (sieve analysis and LSF). Most cement plant uses dry process kiln in clinker production. High raw meal residue which is one the major causes of increased heat consumption were critically considered to determine their corresponding effect on heat consumption.**

During the study, the sieve analysis was conducted to determine the percentage residue for 90µm and 200µm in the raw meal. And the lime saturation factor (LSF) determined using X-ray diffraction machine. All this was carried in the raw meal for production day 1 and production 2. However, the effect of residue and LSF on specific heat consumption was analysed using simplex method of linear programming and duality method. TORA software was used to eliminate human error that could arise using manual calculation and to ensure accuracy. During the sensitivity analysis, the values LSF was varied for 94%, 95% and that of residue for 1.5% and 2% to determine the corresponding on specific heat consumption.

During the sensivity analysis, at 94% LSF and 1.5% residue specific heat consumption of 721.40kcal/kg was obtained. And 729.54kcal/kg for 94% LSF and 1.5% residue. 748.31kcal/kg for 95% LSF and 2% residue. From all the solutions obtained as stated above, it can be seen that the best optimal solution of 721.40kcal/kg of clinker at 94% LSF and 1.5% residue.

By way of extension, the sensitivity analysis done revealed the critical parameter that must be monitored is the material particle size (coarseness) in order to achieved low fuel consumption and increase in clinker production. This allows the particles to react together within the time and temperature conditions in the kiln due to increase in surface area. Coarser particles require a higher reaction temperature and are likely to form relicts of the larger particles they originate from as alite and belite cluster

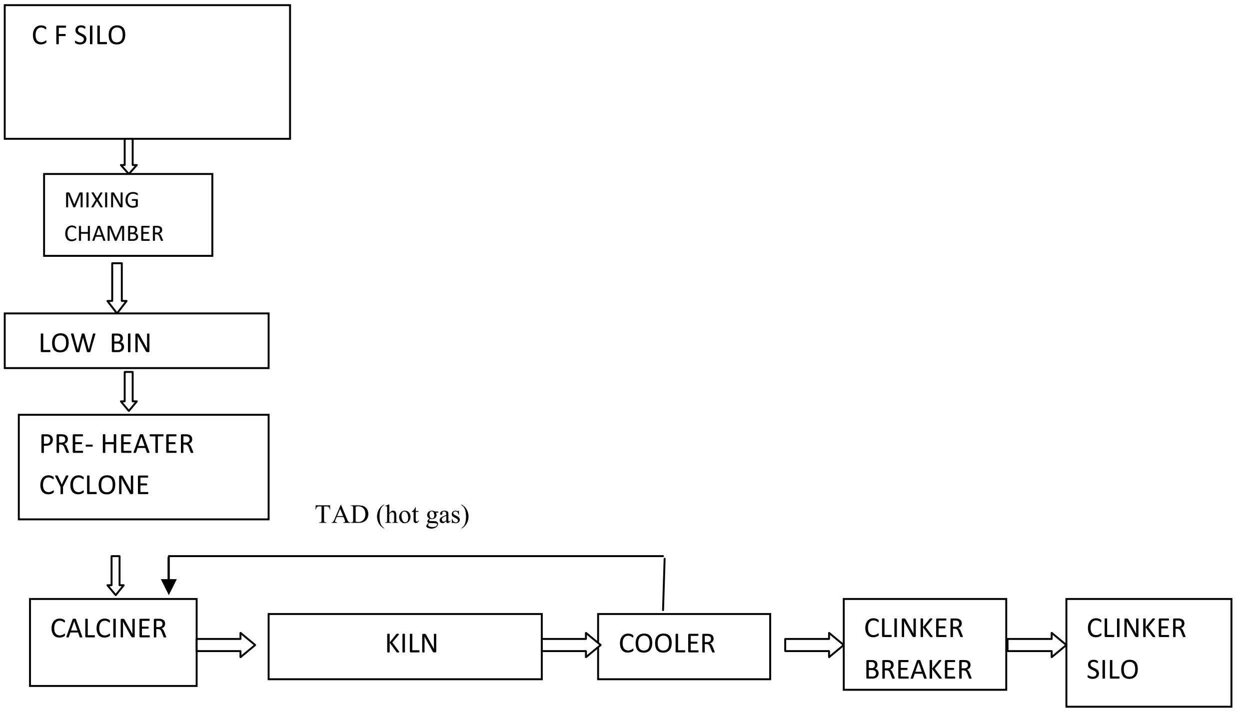
I. INTRODUCTION

Cement manufacturing process involves the blending or grinding of mixture clinker and the additives (high grade limestone and gypsum) together. The quantity of high grade depends on the type of cement to be produced. About 20 to 25% for CEM2 and 5% for CEM1. The quantity of gypsum is about 4 to 5%. Clinker can be blended with porzolana material like fly ash and iron slag in the production porzolana cement.

Clinker production is a pyroproces made through sintering (reaction at high temperature) a mixture of grinded calcareous (limestone) and argillaceous materials (clay and laterite) to a temperature of about 1450°C. It involves a reaction between oxides of calcium, silica, alumina and iron. During this process, partial fusion occurs and nodules called clinker are formed. This highly energy intensive process involves the use of both thermal energy and electrical energy. Though thermal or heat energy constitute the major energy component. The component of cost of heat energy is the highest among all other factors of production. Reduction of heat energy cost will go along way to determine the running cost and profit margin of the cement plant. With depleting energy sources and rising energy costs, it is essential for every cement manufacturer to continuously put in efforts to reduce the heat energy consumption in the manufacturing of cement. Energy reduction not only helps to reduce the production cost of clinker and preserve the mechanical integrity of the equipment, but also helps to reduce the contribution of greenhouse gases to the atmosphere which can result to global warming.

Heat generation in the kiln system involves the conversion specific latent heat in the fuel to free heat and to transfer this heat to the material to form clinker. This heat transfer in the kiln is by radiation as there are no contact between the flame and the material. During the combustion process, right amount of air which is commensurate with fuel supplied in the firing system in other to ensure efficient combustion process. This is achieved by keeping oxygen in both inlet and outlet analyzer in excess above 2%. The threshold temperature for clinkerization reaction is 1450°C while that of calcination reaction in the calciner is 860°C. And also flame must be short to ensure low kiln shell temperature and long refractory life time is maintained (Javed, et al, 2004).The share of energy consumed in a cement clinker kiln plant attains 70-78% of the overall energy consumed in the process of cement production as a whole. The residua (22-30%) is the share of electrical energy. On the other hand, for the burning of the clinker kiln plant, thermal energy represents 92-96% of the required energy and the electrical energy accounts for only 4-8%. Therefore, optimization of pyro process to ensure reduction of specific heat consumption in the kiln plant deserve priority.

CLINKER PRODUCTION PROCESS



The first major reaction after drying is the calcination of limestone (calcium trioxocarbonate) at the temperature of about 860^{o}C . 95%calcination is targeted at the calciner to avoid plugging at cyclone 5.The remaining 5% is accomplish in the kiln. Sintering of the oxide minerals at the temperature at about 1450^{o}C is the next major reaction in clinker production. Detail is as follows;

In the range from 600 to 900 ^{0}C, calcium carbonate decomposes to calcium oxide and carbon dioxide:

$CaCO_3$= CaO + CO_2 ……………… (2.1)

Calcination of magnesium carbonate follows the same pattern, but takes place at lower temperatures:

$MgCO_3$=MgO + CO_2 …………….. (2.2)

From 600^{0}C onwards, several solid reactions occur in parallel with the calcination, for instance:

CaO + Al_2O_3= CaO.Al_2O_3 …………….. (2.3)

The following reactions begin at about 800^{0}C:

CaO.Al_2O_3+2CaO= 3CaO.Al_2O_3 ……………… (2.4)

CaO.Al_2O_3+3CaO + Fe_2O_3= 4CaO.Al_2O_3.Fe_2O_3 ……. (2.5)

CaO.SiO_2+CaO = 2CaO.SiO_2 …………………… (2.6)

Sintering (clinkering) takes place in the presence of liquid phase at temperatures above 1260^{0}C:

CaO + 2CaO.SiO_2 = 3CaO.SiO_2 …………………. (2.7)

A clinker temperature of about 1450^{0}C is required in order to obtain a proper product quality (Tokheim, 1999).

The final stage in clinker production process is the cooling of the clinker and heat recovery. This process has to be performed rapidly at the initial stage of cooling at the control impact system (CIS) in order to keep the desired mineralogical composition of the product; alite (C_2S) tends to decompose if the clinker is cooled too slowly releasing more excess free lime which is detrimental to the quality of the clinker and cement as well. The cooled clinker is mixed with additives such as gypsum and high grade limestone. The quantity of limestone high grade added depend on the type of Portland cement to be produced. Flash ash or iron sulphate is added if producing blended cement. The mix is then ground in cement mills and intermediately stored in cement silos. Finally the cement is packed in bags and sold, or it is sold in bulk (Tokheim, 1999).

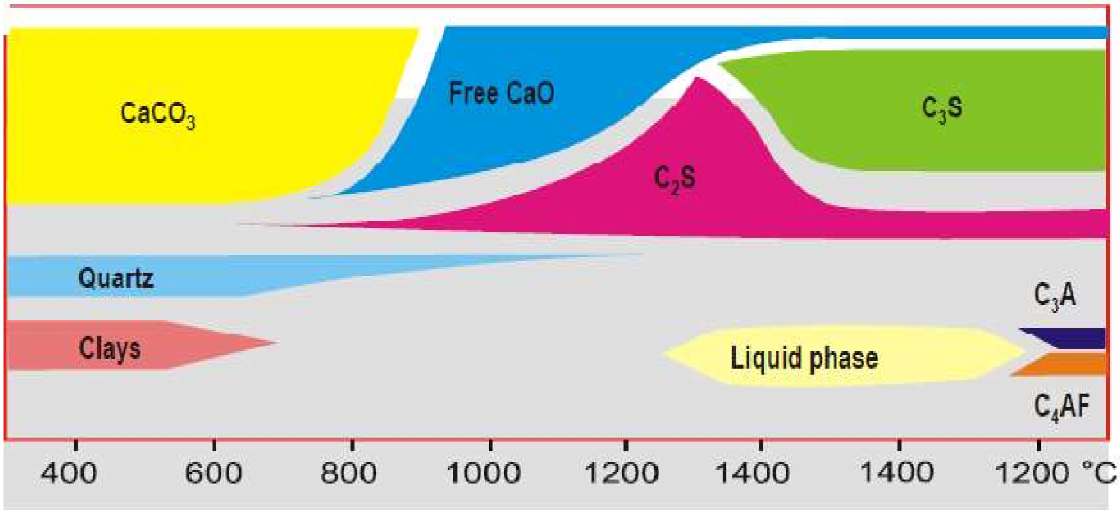


figure 2.1: Transformation of Raw Meal into clinker Production

II. THE CEMENT CLINKER CHEMISTRY

Cement generally is defined as a hydraulic material that hardens on addition of water. Portland cement is also an important building material binder that hardens with the reaction of water. Concrete is a mixture of cement, water and fillers such as sand and stones. The cement clinker is a coarse agglomerate of synthetic minerals that is produced by burning a raw meal, consisting of a selected mixture of raw materials, at a very high temperature in a specialized kiln system. The clinker mostly appears as a dusty granular mixture of dark grey/black particles up to 40mm in size. The cement product is prepared by grinding the clinker with some gypsum and high grade limestone into a fine powder.

The most common ways of characterizing clinker and raw material is by a chemical analysis using X-rays giving the content element expressed as oxides in percentage.

In cement chemistry the following abbreviations are used for some oxides

C = CaO	S = SiO_2	A = Al_2O_3	F = Fe_2O_3	T = TiO_2	M = MgO
K = K_2O	N = Na_2O	H = H_2O	S = SO_3	P = P_2O_5	F" = FeO

Chemical Transformations

Temp. (0C)	**Process**	**Chemical Transformation**
< 100	Drying, elimination of free Water	H_2O (l) → H_2O (g)
100 – 400	Elimination of absorbed Water	
400 – 750	Decomposition of clay with formation of metakaolinite	$Al_4(OH)8 \cdot Si_4O_{10} \rightarrow 2(Al_2O_3 \cdot 2SiO_2) + 4H_2O$
600 – 900	Decomposition of metakaolinite to a mixture of free reactive oxides	$Al_2O_3 \cdot 2SiO_2 \rightarrow Al_2O_3 + 2SiO_2$
600 – 1000	Decomposition of limestone and formation of CS and CA	$CaCO_3 \rightarrow CaO + CO_2$ $3CaO + 2SiO_2 + Al_2O_3 \rightarrow 2(CaO \cdot SiO_2) + CaO \bullet Al_2O_3$
800 – 1300	Binding of lime by CS and CA with formation of C_2S, C_3A and C_4AF	$CaO \cdot SiO_2 + CaO \rightarrow 2CaO \cdot SiO_2$ $2CaO + SiO_2 \rightarrow 2CaO \bullet SiO_2$ $CaO \cdot Al_2O_3 + 2CaO \rightarrow 3CaO \cdot Al_2O_3$ $CaO \cdot Al_2O_3 + 3CaO + Fe_2O_3 \rightarrow 4CaO \bullet Al_2O_3 \cdot Fe_2O_3$
1250 – 1450	Further binding of lime by C_2S to form C_3S	$2CaO_2 \cdot SiO_2 + CaO \rightarrow 3CaO \cdot SiO_2$

Main Clinker Minerals

The oxides of calcium (C), silicon (S), aluminum (A), and iron (F) are the 4 major components that react to form main clinker minerals.

C_3S 50 -65 %	Alite hardens faster than C_2S and contributes to early strength formation. It has a high heat of hydration (500KJ/Kg). It is resistant to Sulphur attack. High content of C_3S will increase strength at all ages.
C_2S 10 – 30 %	Belite hardens slowly and contributes more to the late strength development. It is resistant to Sulphur attack. It has a low heat of hydration (250kj/kg). The content of C_2S in low heat cement used for the castings of large foundations is high.
C_3A 4 – 10 %	Calcium aluminate sets quickly and contributes to the early strength but minimally to the final strength. It has a high heat of hydration liberating a large amount of heat during the final days of hardening (900kj/kg). Cement with low percentage of C_3A are resistant to soil and water containing sulphates. Higher concentration of C_3A can react with sulphate causing and cracking formation exposing more C_3A leading to further penetration of sulphates.
C_4AF 2 – 10 %	Calcium alumina ferrite has minimal effect on the strength on the strengthof the cement contributing only to the final strength of the cement. It gives dark colour to the cement and is avoided in the production of white cement.

C_2S and C_3S make up to the main part (usually 75 – 85 %) of the clinker and are responsible for most of the strength property of the cement. C_3A and C_4AF act as melt in the clinker formation process constituting 10 – 20 % of the clinker.

Any lime which has not reacted with silica, alumina or iron will be left as free lime in the clinker. They are generally unwanted components indicating insufficient burning of the clinker, decomposition of C_3S In the clinker or to high lime saturation factor of the clinker.

III. OPTIMIZATION

Optimization means getting the best condition to either maximize or minimize a given function. Constrained optimization is with limitation, whereas unconstrained optimization is without limitation. Constrained optimization may come as inequality or equality or both.

The word optimum" is Latin, and means the ultimate ideal. Similarly, “Optimus" means “the best." Therefore, to optimize refers to try to bring whatever we are dealing with towards its ultimate state or the best state (Bhattacharjya, 2013).

Optimization is therefore a mathematical discipline which is concerned with finding the maxima and minima of functions, possibly subject to constraints (Bhattacharjya, 2013).

Optimization of heat consumption in a rotary cement kiln has both raw material quality parameter (fines, LSF and SM etc.) and process condition perspective (heat loss). The study of heat consumption is incomplete without taking critical look at the effect this two conditions.

IV. WAYS OF OPTIMIZING HEAT CONSUMPTION IN A ROTARY CEMENT KILN.

1. Proper formulation of raw meal (kiln feed) chemistry. This is done during raw mix design. It is achieved by keeping raw meal chemistry parameters (lime saturation factor (LSF), alumina modulus (AM), silica modulus (SM and Liquid phase) within specification.
2. Process (heat loss). The assessment of heat losses in a system can be achieved by conducting heat balance in the system and comparing it with the design parameter. This is achieved through
    a. Reduction of radiation heat loss through proper refractory application.
    b. Prevention of ingress of false air into the system.
3. Operational. This is achieved by operating the kiln in accordance to standard operation procedures.
    a. Keeping the inlet and outlet excess oxygen at the preheater system within optimum design limit.
    b. 2 to 3% at the kiln inlet and, 2.5 to 3.5% at the preheater outlet.
    c. Optimum heat recuperation from the cooler to the kiln. Maintaining preheater exhaust air temperature with limit (not above 330^0C)
4. low raw meal (kiln feed) residue for 90um and 200um
5. Use of mineralizers. Mineralizers are inorganic compounds which accelerate the Process of reactions in solid phase, liquid phase andsolid-liquid interface. They lead to major impacts on the determination of burning zone, the composition and formation of clinkers minerals (Kacimi *et. al.*. 2006).

Example of mineralizers includes CaF_2 and $CaSO_4$

V. CAUSES OF HIGH HEAT CONSUMPTION DURING KILN OPERATION

i. Low Cooler efficiency. Clinker cooler should be operated efficiently to ensure optimum utilization of secondary air temperature. This is pivotal in ensuring operation stability, heat recuperation and optimization. In this case cooler is operated to ensure secondary air temperature above 900^oc
ii. feed rate variation. This causes instability during operation due frequent change in the volume of material entering the pyro processing system. Most cement kiln is designed to accommodate feed variation not above 10tones per hour.
iii. Incorrect feed chemistry. This has direct effect on product quality and heat consumption. Raw meal chemistry parameters (lime saturation factor (LSF), alumina modulus (AM), silica modulus (SM) and Liquid phase must be kept within specification.
iv. Leakage of air into the system. (False air). Influx of cold air into system lowers the operating temperature thereby requiring more fuel to maintain such temperature. This has direct effect on heat consumption.
v. Over burning. This also results to excessive thermal load on the refractory material which can cause refractory failure. And also clinker of poor grandability(hard clinker) excessive power consumption. This result to high litre weight and very low free lime (FCaO).
vi. High residue. The particle size of the raw meal has direct effect on the rate of reaction of its component oxides.

Clinker Production

Raw Materials		Clinker
67% C		67% C_3S
22% S		14% C_2S
3.5% A	$\longrightarrow$	5% C_3A
3.5% F	1450°C	10% C_4AF
4% Impurities		4% Impurities
100%		100%

VI. EFFECT OF RAW QUALITY PARAMETER (LSF AND RESIDUE) TO HEAT CONSUMPTION

Considering the design LSF 94%, residue of 1.5% on 200um and design upgraded capacity of the plant of 7000TPD of clinker. Investigation on the effect this quality parameter was achieved by application of linear programming. Applying simplex method of linear programming gives the result as stated below.

Presentation of Data Collected During Kiln Operation

Data collected during kiln operation are also presented below and used for the calculation of heat consumed in Kcal/Kg of clinker:

PRODUCTION DAY **1**

Clinker Produced (TPD): 6811tons = $6811*10^3$kg

Gas Used at the Calciner (NM3): 367538

Gas Used for Burning in the Kiln (NM3): 180852

Total Gas used per day (NM3): 548390

Heat Consumed (Kcal/Kg Clinker) H is calculate as;

H = fuel consumed (gas) * calorific value (CV) / production

$H = 548390 * 9019 / 6811*10^3$

H = 726 kcal/kg

PRODUCTION DAY **2**

Clinker Produced (TPD): 6802tons = $6802*10^3$kg

Gas Used at the Calciner (NM3): 370449

Gas Used for Burning in the Kiln (NM3): 181456

Total Gas used per day (NM3): 551905

Heat Consumed (Kcal/Kg Clinker) H is calculate as;

$H = 551905 * 9019 / 6802*10^3$

H = 732 kcal/kg

Presentation of Data in Linear Programming Form

X_1 = PRODUCTION DAY 1

X_2 = PRODUCTION DAY 2

H = heat consumption by the Kiln (Kcal/Kg)

LSF = Lime Saturation Factor (%)

S = Kiln feed fines (Sieve %)

TPD = Quantity of Clinker Produced in tons per day

TABLE 4.4: Linear Programming Table

	X_2	X_3	
H	726	732	
TPD	6811	6802	14000
LSF	94.6	94.4	94
S	1.8	1.6	1.5

It is expected the total production per day on production should be 14000 tons with LSF 94% and Sieve 1.5% using either gas or LPFO as fuel for heat generation.

Our Objective function equation is developed from Table 4.5.

Minimizing Using Simplex Method

This research seeks to minimize the heat consumption (H) using Mark A. Schulze, 1998, solution method.

$$\mathbf{H} = + 726X_1 + 732X_2 \ldots\ldots 4.1$$

Subject to the following constrains:

$$6811X_1 + 6802X_2 \leq 14000$$

$$94.6X_1 + 94.4X_2 \geq 94$$

$$1.8X_1 + 1.5X_2 \geq 1.5$$

$$X_1 \geq 0,\ X_2 \geq 0,$$

Adding Slacks Values:

$$6811X_1 + 6802X_2 - S_1 = 12000 \ldots\ldots\ldots\ldots 4.2$$

$$94.6X_1 + 94.4X_2 + S_2 = 94 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 4.3$$

$$1.8X_1 + 1.5X_2 + S_3 = 1.5 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 4.3$$

Where S_1, S_2 and S_3 are slacks variables

The problem was therefore solved using simplex method of linear programming (TORA) and the solution was obtained as 721.40kcal/kg of clinker.

Applying Sensitivity Analysis

Our task is to conduct sensitivity analysis by independently investigating each of a set of changes (detailed below) in the original problem. For each change, we will use the fundamental insight to revise the final set of equations (in tableau form) to identify a new solution and to test the new solution for feasibility and (if applicable) optimality (Nagesh, 2004)

Sensitivity Analysis at Target Residue of 1.5% and LSF of 94 %

Final Tableau (Appendix):

BASIC	Sx_5	Rx_6	Rx_7	SOLUTION
H (min)	0.00	-93.33	- 100.00	721.40
Sx_5	1.00	-72.00	0.00	7232.20
SX_4	0.00	0.02	-1.00	0.29
X_1	0.00	0.01	0.00	0.99

TABLE 4.5.1

$$\begin{pmatrix} SX_5 \\ SX_5 \\ X_1 \end{pmatrix} = \begin{pmatrix} 1.00 & -72.00 & 0.00 & 14000 \\ 0.00 & 0.02 & -1.00 & 94 \\ 0.00 & 0.01 & 0.00 & 1.5 \end{pmatrix} \geq \begin{pmatrix} 0 \\ 0 \\ 0 \end{pmatrix}$$

The current basic feasible solution is (Sx_5,SX_5, X_1) = (7232.20, 0.29, 0.99),which has an objective function value of 721.40.

Sensitivity Analysis at Target Residue of 2% and LSF of 94 %

Final Tableau (Appendix):

BASIC	SX_5	Rx_6	Rx_7	SOLUTION
H (min)	0.00	-94.23	0.00	742.54
SX_5	1.00	-72.00	0.00	7232.20
X_1	0.00	0.00	0.00	0.99
RX_7	0.00	-0.02	1.00	0.21

TABLE 4.5.2

The current basic feasible solution is (Sx_5, X_1, RX_7) = (7232.20, 0.99, 0.21), which has an objective function value of (H) =721.40.

Sensitivity Analysis at Target Residue of 2% and LSF of 95 %

Final Tablue

BASIC	SX_5	Rx_6	Rx_7	SOLUTION
H (min)	0.00	-94.23	0.00	748.31
Sx_5	1.00	-72.00	0.00	7160.20
X_1	0.00	0.01	0.00	1.00
Rx_7	0.00	-0.02	1.00	0.19

TABLE 4.5.3

The current basic feasible solution is (Sx_5, X_1, RX_7) = (7160.20, 1.00, 0.19), which has an objective function value of (H) =748.31.

Sensitivity Analysis at Target Residue of 1.5% and LSF of 95 %

BASIC	SX_5	RX_6	RX_7	SOLUTION
H(min)	0.00	-92.33	-100.00	729.07
SX_5	1.00	-72.00	0.00	7160.20
SX_4	0.00	0.02	-1.00	0.31
X_1	0.00	0.01	0.00	1.00

TABLE 4.5.4

The current basic feasible solution is (Sx_5, SX4, X_1) = (7160.20, 0.31, 1.00), which has an objective function value of (H) =729.07

Summary

LSF	RESIDUE	X_1	H(min)
94	1.5	0.99	721.40
95	1.5	1.00	729.07
94	2	1.00	742.54
95	2	1.00	748.31

LSF	RESIDUE	H(min)	H(min) DEVIATION
94	1.5	721.40	0
95	1.5	729.07	-7.67
94	2	742.54	-21.14
95	2	748.31	-26.91

TABLE 4.5.5

Effect of Change in Quality Parameter (LSF and Residue) on the Value Heat Consumption (H)

1, From the table above increase in LSF by 1% (94 to 95 %) at constant residue of 1.5um will result to an increase in heat consumption (H) of 7.67 kcal/kg of clinker (729.07 – 721.40).

2, Also, from the table above increase in residue by 0.5um (1.5 to 2 um) at constant LSF of 94% will result to an increase in heat consumption(H) of 21.14 kcal/kg of clinker (742.54 – 721.40).

3, An increase in both LSF by 1% and residue by 0.5um will result to an increase in heat consumption by 26.91 kcal / kg of clinker (748.31 – 721.4).

From the data above, it can be seen that increase in residue has more resultant effect on heat consumption than that of LSF. Though increase in LSF of the kiln feed will lead to a resultant increase in the value of C_3S which impact positively on quality of clinker and as well on the strength of the cement.

VII. CONCLUSION

The kiln is the most critical equipment in cement production plant. Also the cement production process is a pyro process which demand large amount heat which constitute the highest cost of production as seen in the literature review. Therefore, attention should give to both the process of heat generation and consumption to ensure optimization of the process. Apart from reduction in heat consumption, optimization of a pyro process has other benefit which include prevention of global warming and preservation of mechanical integrity of equipment.

The DCP kiln under study was designed byFLSmidth with upgraded capacity of 7000tpd of clinker and specific heat consumption of 740kcal/kg of clinker. During the study both the quality parameter (LSF and Residue) and process condition (heat loss) were put into consideration. After optimization analysis, heat consumption was reduced to 721.40Kcal/Kg of Clinker; keeping Kiln feed chemistry for LSF at 94% , and residue at 1.5%.

However, from further sensitivity analysis, it was observed that an increase in residue has more resultant effect (increase) on the specific heat consumption than that of LSF with no benefit of the clinker quality. Also looking at the process condition (heat loss) , from the data obtained heat loss through the preheater exhaust gas constitute the highest source of heat loss. The process of minimize are as explain in the review. All this is done to ensure production of good quality of clinker at a reasonable price and consequently the cement.

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