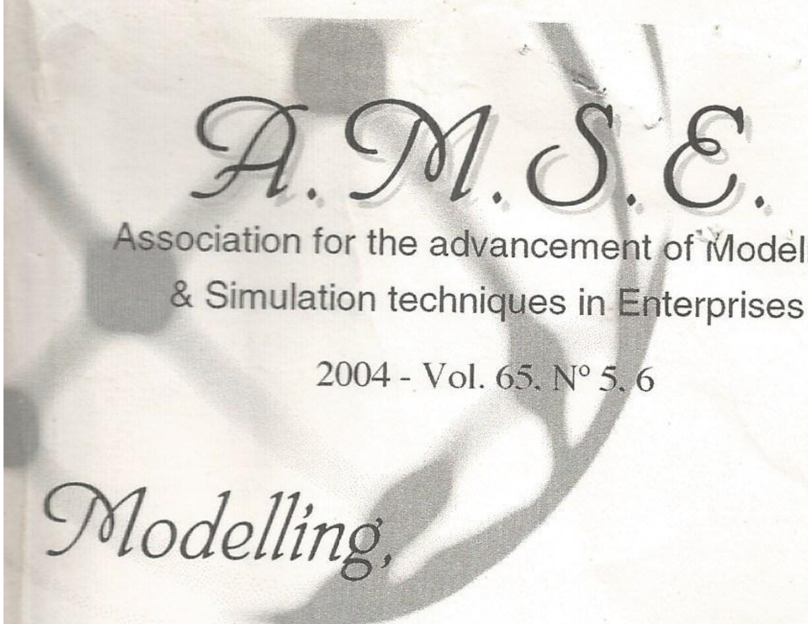

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Design, Construction and Testing of a Wood-Fired Mini Lime Plant

O.J. Okegbile, S.O. Ubokwe, Shaba Goshie

Dept of Mechanical Engineering, Federal University of Technology,
P.M.B. 65, Minna, Nigeria

Abstract

Due to the rural-based nature of the limestone deposits in Nigeria, a wood-fired lime kiln was designed and constructed with local refractory bricks to be used in a rural setting. The bricks were produced from a mixture of Kaolin and Sawdust. They were allowed to dry in the sun for three days and then fired at a temperature of 1000°C for five hours. Experiments carried out on the calcination of limestone to lime in the kiln shows that limestones of between 3.00 – 5.00mm sizes calcined faster due to quicker heating up and faster escape of carbon dioxide from the limestone. Duration of firing greatly affected the lime yield. The average yield is 52.17%, while the percentage of CaO in the lime is 99.7% which indicates a very high degree of calcination to lime from limestone.

Keywords

Limestone, lime, kiln, refractory bricks, kaolin, sawdust, temperature, calcination, carbon dioxide, average yield.

1.0 Introduction

Lime is used extensively in Nigeria. Some of the uses are – for water and sewage treatment, leather processing, paper making, fertilizer manufacture, cosmetics, cement production and in iron and steel industry. The country's demand for lime was estimated by Urhoghide and Nwanze (1988) to be 700,000 tones per year in 1988. Inspite of the wide application of lime in Nigeria, it is largely imported into Nigeria. The technology of lime production is simple. It involves the calcination of limestone at a temperature of 900°C in a kiln. The primary raw material which is limestone occurs abundantly in many states in Nigeria like Cross River, Benue, Edo, Kogi, Niger, Anambra and Sokoto States.

Most of the deposits are located in rural areas where there is no electricity and other conventional fuels like coal, coke, oil and gas for firing. Hence the need for this design of a locally constructed kiln that could use fuel wood which is locally available to calcine limestone into lime.

Kiln is the furnace widely used for calcination of lime. For a wood-fired kiln, there are four essential sections according to Francis and Peters (1980), viz fireplace where wood is burnt, hearth in which the raw materials to be heated are placed, a grate, and finally the draught producer consisting of a chimney. The chimney creates a draught by virtue of the lower density of the hot gases compared to the surrounding atmosphere. Some of the characteristics required of the refractory bricks for kiln lining as given by Gulu (2000) are thermal stability, mechanical strength, refractoriness and thermal conductivity. Kaolin refractories have sufficiently these properties and according to Gulu (2000), they possess refractoriness between 1,580 and 1770°C.

Calcination is a single solid reaction involving one reactant decomposition to produce solid and gas. A theoretical analysis given by Boyton (1980) on the calcination process shows that 100g of $CaCO_3$ produces 56g of CaO and 44g of CO_2. The carbon dioxide can be limiting factor in this process. Therefore, it must be removed as fast as it is produced in order to prevent the build-up of high CO_2 pressure, which can reverse the reaction and cause low yield of CaO. Boyton (1980) further outlined three essential factors in the kinetics of limestone decomposition as follows:- the limestone must be heated to the dissociation temperature. This temperature must be maintained for a certain duration of time. The carbon dioxide gas that is evolved must be removed. Research effort by the National Research Institute for Chemical Technology, Zaria, Nigeria, in the design and construction of an oil-fired kiln of 2,000kg capacity per day has not been very successful. There were some design problems encountered during the test running of the equipment. Some of the problems of the kiln operations were highlighted by Ugwu and Bello (1999) as follows:- 1) lack of loading and discharge mechanism, 2) lack of carbon dioxide suction mechanism, 3) lack of air and fuel meters, 4) poor arrangement of burners that led to backfiring of the kiln, and 5) lack of manhole for re-lining of the walls during maintenance, and the capacity utilization is only 25%. The problems enumerated above led to the consideration of this design which is wood-fired kiln. A survey carried out by Francis and Peters (1980) noted that wood may be burnt as fuel in semi-tropical and tropical countries where forests are available cheaply. The heating value of a seasoned wood as given by Shuets et al (1980) is 11720 kJ/kg. Solid fuel like wood according to Francis and Peters (1980) possesses advantages like cheapness, capacity for storage in large quantities on flat surfaces. On this basis, wood is used as the fuel in this design. The result of this work is very encouraging and the kiln can be used in the rural settings where there are limestone deposits to create employment and reduce rural-urban drift. This can create employment in rural areas thereby alleviating poverty and bringing investment and development to such communities.

2.0 Design analysis

2.1 Design Analysis for Air required for combustion and products of combustion using theoretical Air.

The amounts of oxygen and air required for the combustion of 1kg of each combustible element of the fuel are obtained and tabulated in Table 1.

$$C + O_2 + 3.76N_2 = CO_2 + 3.76N_2 \qquad \text{-- 1.1}$$

$$12\text{kg of } C + 32 \text{ kg of } O_2 + 105.3\text{kg of } N_2 = 44\text{kg of } CO_2 + 105.3\text{kg of } N_2$$

$$1\text{kg of } C + 2.66 \text{ kg of } O_2 + 8.78\text{kg of } N_2 = 3.66\text{kg of } CO_2 + 8.78\text{kg of } N_2$$

$$2C + O_2 + 3.76N_2 = 2CO + 3.76N_2 \qquad \text{-- 1.2}$$

$$24\text{kg of } C + 32 \text{ kg of } O_2 + 105.3\text{kg of } N_2 = 56\text{kg of } CO + 105.3\text{kg of } N_2$$

$$1\text{kg of } C + 1.33\text{kg of } O_2 + 4.39\text{kg of } N_2 = 2.33\text{kg of } CO + 4.39\text{kg of } N_2$$

$$2H_2 + O_2 + 3.76N_2 = 2H_2O + 3.76N_2 \qquad \text{-- 1.3}$$

$$4\text{kg of } H_2 + 32 \text{ kg of } O_2 + 105.3\text{kg of } N_2 = 36\text{kg of } H_2O + 105.3\text{kg of } N_2$$

$$1\text{kg of } H_2 + 8 \text{ kg of } O_2 + 26.33\text{kg of } N_2 = 9\text{kg of } H_2O + 26.33\text{kg of } N_2$$

$$S + O_2 + 3.76N_2 = SO_2 + 3.76N_2 \qquad \text{-- 1.4}$$

$$\text{kg of } S + 32 \text{ kg of } O_2 + 105.3\text{kg of } N_2 = 64\text{kg of } CO_2 + 105.3\text{kg of } N_2$$

$$\text{of } S + 1 \text{ kg of } O_2 + 3.29\text{kg of } N_2 = 2\text{kg of } SO_2 + 3.29\text{kg of } N_2$$

Table 1: Table for Air required for combustion and Products of Combustion using theoretical Air.

Combustion Element	Quantity of air, components, Products of combustion per kg of ele							
	O_2	N_2	Air	CO_2	CO	N_2	H_2O	SO_2
Carbon	2.66	8.78	11.44	3.66	-	8.78	-	-
Carbon	1.33	4.39	5.72	-	2.33	4.39	-	-
Hydrogen	8	26.3	24.33	-	-	26.33	9.0	-
Sulphur	1	3.29	4.29	-	-	3.29	-	2.0

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2.2 Design Analysis for Heat losses

2.2.1 Analysis of heat loss in dry flue gases.

Heat loss in dry flue gases can be calculated using equation 1.5

$$Q = W_g(T_g - T_a) \times C_d \qquad 1.5$$

where, W_g is the weight of dry flue gases, kg

T_g is the temperature of exit gases, K

T_a is the temperature of inlet air, K

C_d is the average specific heat capacity of dry flue gases, kJ/kgK

2.2.2 Analysis of heat loss due to moisture in dry flue gases.

Heat loss due to moisture in dry flue gases can be calculated using the equation 1.6

$$Q_w = m\{(100 - T_a)C_{pl} + h_{fg} + C_{pv}(T_g - 100)\} \qquad 1.6$$

Where, m is the mass of moisture in 1 kg of fuel, kg

T_a is the temperature of inlet air, K

T_g is the temperature of exit gases, K

h_{fg} is the latent heat of evaporation of water above 100°C = $2.25\,\mathrm{MJkg^{-1}}$

C_{pl} is the specific heat of water below 100°C = $4.19\,\mathrm{kJ\,kg^{-1}\,K^{-1}}$

C_{pv} is the average specific heat of steam above 100°C = $2.09\,\mathrm{kJ\,kg^{-1}\,K^{-1}}$

2.2.3 Analysis of Heat loss by Conduction and Convection through the wall of the kiln.

Heat loss by conduction and convection can be calculated using equation 1.7

$$Q_c = \frac{T_h - T_a}{\frac{1}{h_h A} + \frac{L}{kA} + \frac{1}{h_a A}} \qquad 1.7$$

Where, T_h is the temperature of hot gases inside kiln, K

T_a is the temperature of inlet air, K

h_h is the convective heat transfer coefficient of gases inside the kiln, W/m^2K

k is the thermal conductivity of the wall of kiln, W/mK

h_a is the convective heat transfer coefficient of inlet air, W/m^2K

A is the area of wall normal to heat flow, m^2

2.3 Analysis of Heat consumed by limestone

Heat consumed by limestone can be calculated using equation 1.8

$$Q = mCdt \qquad 1.8$$

Where, m is the mass of limestone, kg

C is the specific heat capacity of limestone, $kJ\ kg^{-1}\ K^{-1}$

dt is the change in temperature, K

2.4 Analysis of Purity of lime

According to Boyton (1980), Weisz arbitrarily designates the limestone – lime quality factor as A known as purity of lime. If the chemical analysis of the lime is known, then A can be calculated using equation 1.9

$$A = \frac{\%CaO \times 1.785}{(\%CaO \times 1.785) + (\%MgO \times 2.092)} \times \frac{100}{1} \qquad 1.9$$

Where, %CaO is the percentage of CaO in lime

%MgO is the percentage of MgO in lime

1.785 is a theoretical conversion factor from CaO to $CaCO_3$

2.092 is a theoretical conversion factor from MgO to $MgCO_3$.

2.5 Analysis of number of refractory bricks required for the construction.

Figure 1.1 shows the brick wall elevation of the front and the rear view of the kiln. It is divided into four segments, viz A – D and area of each segment can be calculated as shown in equations 1.9 – 1.12.

Area of A = l x b 1.10

Area of B = l x b 1.11

Area of C = l x b 1.12

Area of D = $\frac{1}{2} r^2(\theta - \sin\theta)$ 1.13

Where, θ is in radians

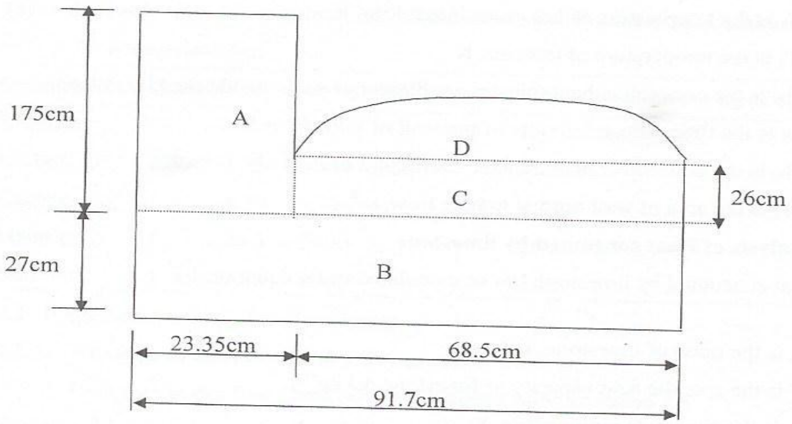

Fig. 1.1: Brick Wall Elevation of Front and Rear View.

Figure 1.2 shows the brick wall elevation of the left side of the chimney, while Figure 1.3 shows the brick wall elevation of right side of the chimney and Figure 1.4 shows brick wall elevation of right side of kiln. Figure 1.5 shows area of top plan and Figure 1.6 shows effective area of the brick.

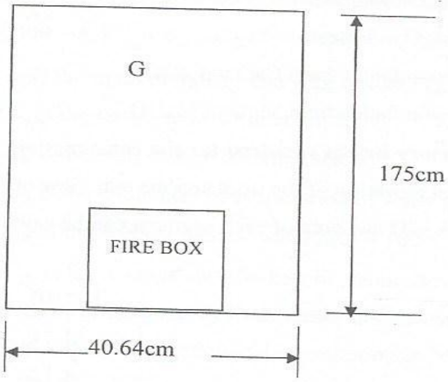

Fig. 1.2: Brick wall elevation of left side of chimney.

$$\text{Area of } G = l \times b \qquad 1.14$$

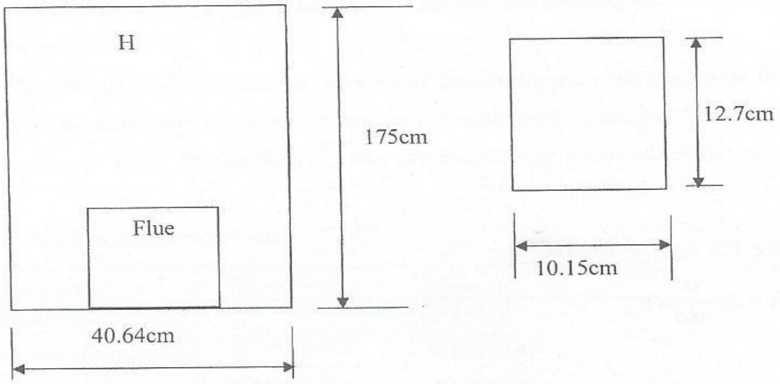

Fig. 1.3: Brick wall elevation of right side of chimney.

Area of H = l x b 1.15

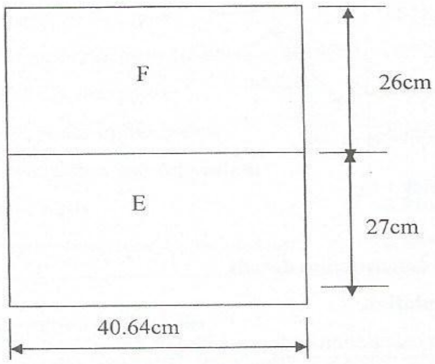

Fig. 1.4: Brick wall elevation of right side of kiln.

Area of E = l x b 1.16

Area of F = l x b 1.17

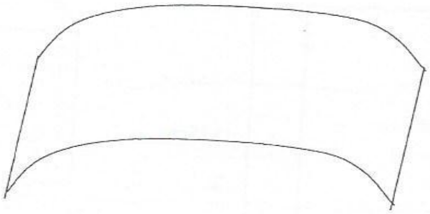

Fig. 1.5: Area of top plan

$$A = 2\pi \frac{\theta}{360} \times b \qquad 1.18$$

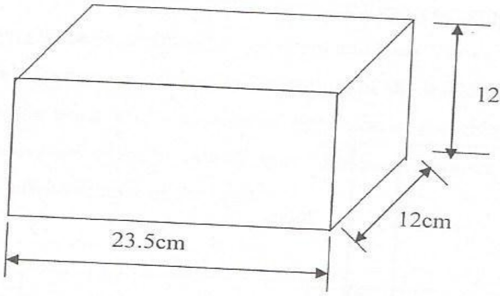

Fig 1.6: Effective area of the Brick.

$$A = l \times b \times h \qquad 1.19$$

3.0 Calculated results and construction details.

3.1 Results of Design Calculation.

The results of the design calculations are presented in Table 2.

3.2 Production of Refractory Bricks

Known quantities of kaolin and sawdust were mixed with known quantity of water. The mixture was covered with tarpaulin and left for three days. After three days, the mixture was loaded into a brick-moulding machine and pressed with a known pressure to obtain the required shape. The bricks were allowed to dry. The brick looks brownish in colour when removed from the moulding machine and light brown when it was dried; this was an indication that the water content has been evaporated. The dried moulded bricks were arranged inside a wood fired kiln and fired at a temperature of 1000°C for about five

hours. The sawdust was burnt and the products of combustion were expelled from the refractory bricks, which are light in weight and have desired porous structure. The bricks were allowed to cool. The refractory bricks are suitable for temperatures of up to 1500°C.

Table 2: Results of design calculations

Parameters	Quantity
Total area of kiln	$3.348m^2$
Effective area of brick	$0.00282\ m^2$
Total number of bricks required	131 bricks
Mass of air required for combustion	4.6190kg air/kg fuel
Total wet product of combustion	5.607kg
Total dry product of combustion	5.029kg
Total water vapour in flue gases	0.57kg
Heat content of seasoned wood (Shuets et al,1980)	11.720MJ/kg
Heat loss due to dry flue gases	2.7208MJ/kg
Heat loss due to water in flue gases	2.0449MJ/kg
Heat loss by conduction and convection through the kiln walls	0.11MJ/s
Heat consumed by limestone for calcination	6.8443MJ/s

3.3 Construction of the Kiln

The kiln was lined with the locally produced refractory bricks. The lining of the bricks were done in such a way that each course overlays the next. The mortal used for laying the bricks is a mixture of kaolin, sawdust and water which was allowed to stay overnight. The mortar has advantage over cement mix because it is easy to dismantle the brickwork which is overlaid with mortar.

One hundred and nineteen refractory bricks were used in building the kiln. Effective area of a brick is 0.235m x 0.12m. The key parameters of the kiln have volumes as follows:- kiln chamber has 0.2544 x 0.765 x 0.27m, bag wall is 0.2544m x 0.076m x 0.12m, chimney is 0.254m x 0.1016m x 1.75m and finally flue is 0.1016m x 0.12m.

3.4 Heat Analysis of the kiln

The basic equation is

Heat input = Heat output 1.20

Table 3 below shows the heat balance of the kiln.

Table 3: Heat balance of the kiln.

Heat input items	MJ/kg	%	Heat output items	kJ	%
1. Physical heat content of seasoned wood (Shuets et al, 1980)	11.72	100	1.Heat required for calcination	6.8843	58.74
			2.Heat loss to dry flue gases	2.7208	23.22
			3.Heat loss due to water in flue gases	2.0049	17.11
			4.Heat loss by conduction and convection through the kiln walls	0.11	0.93
Total heat input	11.72	100	Total heat output	11.72	100

4.0 Testing of the Kiln, performance results and discussion.

4.1 Testing of the Kiln

Limestone was crushed and weighed on a scale and required quantity to be calcined was charged into the wood fired kiln chamber which can withstand a temperature of about 1500°C. Seasoned fuel woods were weighed and fed into the fire box and ignited. Combustion of the woods takes place in the fire box, the heat generated in the fire box is pulled over a bag wall into the kiln chamber by drought produced by the chimney.

The kiln was fired in three batches and an average temperature of 1000.8°C was recorded for each batch during the firing. Stoking of the fire box with wood was done at regular basis to ensure continuous burning of the wood. This is to enable a uniform rise in temperature. Calcination of the limestone took place in the kiln chamber with the aid of the heat produced by the wood fuel. Exhaust gases with carbon dioxide liberated from the limestone go out of the kiln as flue gases through the chimney. Ash produced during firing was removed from the fire box regularly to discourage the blockage of the fire box.

After calcination has taken place, the lime produced was removed from the kiln through the kiln door and the resulting lime weighed after cooling. Figures 2.1 to 2.3 show the temperature profile in the kiln with time for batches one to three of the fired limestone. Each graph has two components i.e. temperature inside the kiln and that of the flue gases. Chemical analysis of the initial limestone (raw material) and the calcined lime in three batches is given in Table 4. In each of the batches, quantity of limestone, duration of calcination and limestone sizes were varied.

4.2 Results and discussion

As shown in Figure 2.1, the temperature of the flue gases rose rapidly to 768°C and later decreased to 710°C, then continued rising again. This suggest that between these temperatures, active calcination process took place, and this helps to determine the residence time of the limestone in the kiln chamber. The product yield of 58.84% is the highest compared to yields of batches B and C. This could be as a result of longer duration of firing in batches B and C.

Quantity of limestone charged = 8kg
Lime produced = 4.71kg (58.84%)
Amount of wood used for firing = 65.5kg
Duration = 280 minutes

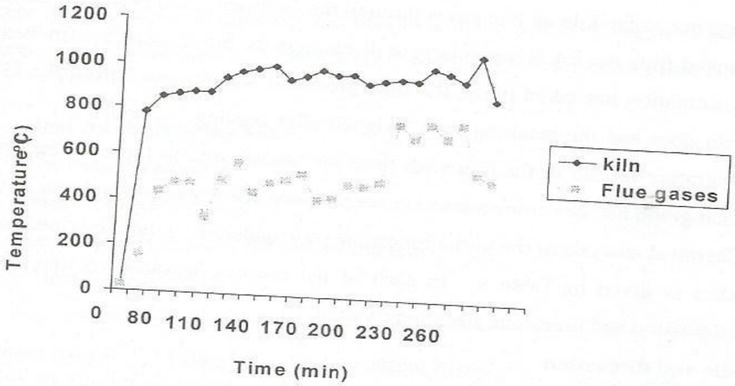

Fig. 2.1: Temperature profile of Batch A

In the batch referred to as batch B, the product yield is 51.24% which is less than the yield in batch A. This could be as a result of shorter duration of firing when compared to that of batch A. It can be seen that the temperature profile of the kiln in batch A and B has similar pattern. This is because, the firing of the kiln started from the ambient temperature of 30°C. The flue gases temperature rose to 768°C and later decreased to 580°C, then continues to rise as shown in the two diagrams (Figures 2.1 and 2.2).

Quantity of limestone charged = 8.5kg

Lime produced = 4.36kg (51.24%)

Amount of wood used for firing = 53kg

Duration = 220 minutes

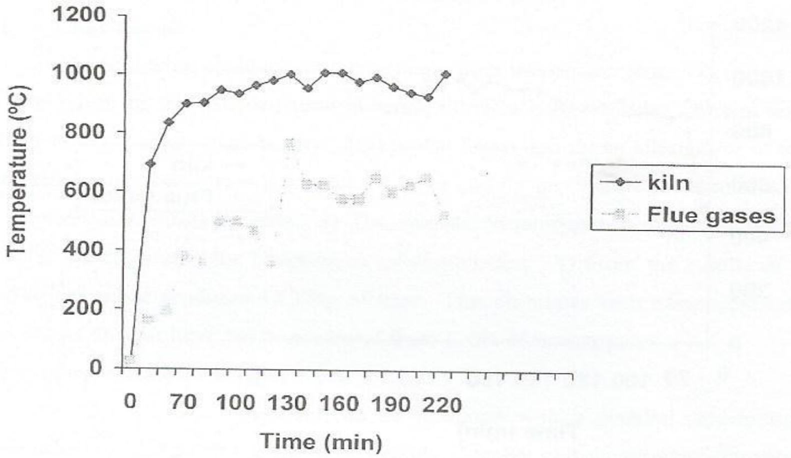

Fig. 2.2: Temperature profile of Batch B

The product yield in batch C was found to be the lowest (47.83%). This may be due to low temperature attained. The diagram in Figure 5.3 shows that the average temperature of the flue gas (CO_2) at calcination point is 370°C and above, and the highest temperature of the flue gases in the kiln is 778°C. The temperature profile for batch C in Figure 5.3 is different from that of batch A and B for both flue gases and kiln. This is because the firing was done from 500°C

Quantity of limestone charged = 9kg

Lime produced = 4.30kg (47.83%)

Amount of wood used for firing = 49kg

Duration = 220 minutes

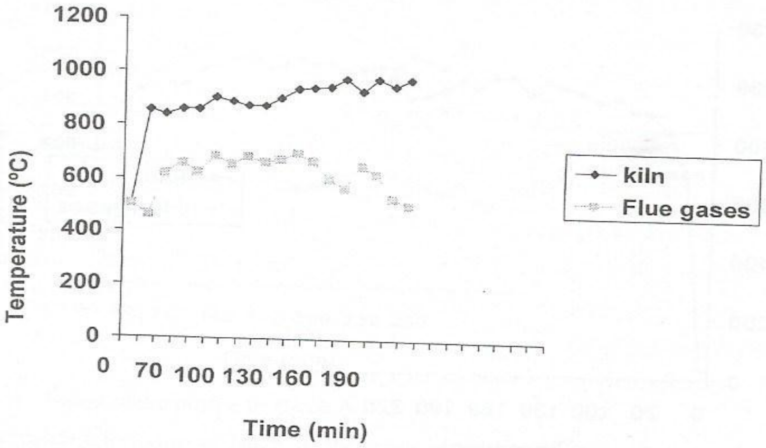

Fig. 2.3: Temperature profile of Batch C.

From the result of chemical analysis in Table 4, the percentage CaO in the original sample of limestone is 80%. The percentage of ferrous oxide in the calcined sample reduced drastically. Other oxides both in the original sample and calcined sample have negligible percentage. Physical observation of the original sample of limestone and the calcined sample shows that the original sample has dark grey colour while the calcined sample has milky colour. The chemical analysis of the limestone and the calcined lime is as presented in Table 4.

Table 4: Chemical Composition of Limestone and Calcined Lime.

Oxides	Percentage in original Limestone samples	Percentage in batch A	Percentage in batch B	Percentage in batch C
SiO_2	0.85	0.50	0.55	0.58
TiO_2	0.04	0.03	0.02	0.02
CaO	80.54	86.29	86.00	86.15
MgO	0.30	0.22	0.20	0.24
Na_2O	0.03	0.02	0.01	0.01
K_2O	0.23	0.30	0.38	0.44
Fe_2O_3	0.99	0.60	0.69	0.65

5.0 Conclusions and suggestion for further work

5.1 Conclusions

The following conclusions can be made from this project work:-

1) The purity of the calcined lime in terms of %CaO for the three batches was above 99.7% and it is a very high quality. 2) It is also found that the smaller grains of limestone between 2mm – 5mm grain size calcined faster and the productive duration of calcination is between 200 – 280 minutes. 3) The calcination temperature ranges between 900 to 1110°C which is also the temperature of dissociation. 4) From the results of the test, 25.5kg limestone produces 13.37kg of lime. This correlates with theoretical calculation that shows 56% of lime can be produced from 100% of limestone.

5.2 Suggestion for further work

A kiln of larger capacity can be designed with a detailed calculation of the geometric parameters of the fire box, heating chamber and the chimney for more firing efficiency. The charging of the raw materials and the discharging of the finished product can then be machanised.

Refrences

1. Boynton R. S. "Chemistry and Technology of lime and limestone" Wiley Interscience Publisher, London, 1980.
2. Francis W. and Peters M. C. "Fuels and Fuel Technology" Pergamon Press Ltd., London. 2nd Edition, 1980.
3. Gulu H. A. "Design and Construction of oil fired kiln for lime production" PGD project report, Department of Mechanical Engineering, F. U. T. Minna, pp 35 – 45, 2000.
4. Shuets I. T., Tolubinsky N. F. , Neduzhy I. A. and Sheludco I. M. "Heat Engineering" Mir. Publishers, Moscow. 2nd Edition, pp 139 – 163, 1980.
5. Ugwu J. O. and Bello J. B. "Production of Lime using local designed Lime kiln" Research Report NARICT Zaria, Nigeria, pp 35 – 45, 1999.
6. Urhoghide S. O. and Nwanze A. O. "The utilization of local limestone for lime production (Experience at Delta Steel Company, Ovwian —Aladja)" Journal of the Nigerian Society of Chemical Engineers vol. 7, No. 2, pp 80 – 88, 1988.

7. Holman J. P. "Heat Transfer" 9th edition, Mc Graw-Hill Int. Book Co., Tokyo, 2001.
8. Fathy H. "Architecture for the poor" Chicago University Press, Chicago, 2000.
9. Schneider P. J. "Conduction Heat Transfer" Addison-Wesley Publishing Co. Inc. Reading, Mass., 1959.
10. Karlekar B. V. and Desmond R. M. "Heat Transfer"2nd edition, Prentice Hall of India, 1989.