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SEMI-BATCH INDUSTRIAL SIZE VERTICAL SHAFT LIME KILN DESIGN

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ABSTRACT

The work embraced a modified design, construction and test running of an industrial size vertical shaft lime kiln. The lime kiln was 3.0 m tall with internal diameter of 0.6 m. It was designed for a maximum charging of 1.5 tonnes of limestone, while about 250 kg of lime was to be discharged every three hours. This offered the system a semi-batch process. The stability and integrity of the plant installation was good based on the thermal insulation. A calcination temperature of about 1200 ℃ as required to calcine Jakura limestone in the kiln, and there was adequate thermal insulation to maintain low outer wall temperature. The serious backfiring, that is usually encountered in the operations of locally fabricated vertical shaft lime kilns due to poor draft was minimized. More so, the high down time encountered during the charging and discharging of most local kilns was also minimized. The calcined lime was analysed and the available lime from the product was 86 wt%, while the pH raged from 11.0 to 12.5. The settling rate of the product lime in distilled water was low.

Keywords: Backfiring, calcination, Jakura, kiln, limestone, semi-batch

INTRODUCTION

Vertical shaft lime kiln is an equipment used for decarbonation of limestone. This is a reaction, which occurs above 900 ℃. The calcination process basically removes carbon (IV) oxide from the limestone to produce calcium (II) oxide known as quick lime or hydrated lime when water is added [1]

Limestone known as calcium carbonate is a solid mineral which is naturally hard inorganic substance that possesses definite composition and atomic structure. It also has economic value. It is derived from the earth's crust like other solid minerals and very useful for our technological advancement [2]. It is abundantly deposited in Nigeria [3]. The deposit is invariably associated with shale units and as a result, it ranges in composition from calcareous to pure limestone which is used to produce the quick lime [4].

Lime, calcium (II) oxide has numerous uses. Besides its sanitary and environmental uses as major water treatment chemical, it is used in chemical and metallurgical industries. It is also used in agriculture, construction and petroleum [5], Inspite of the large demand of lime as a result of its numerous uses, there has not been practicable technological design and construction to cut down the nation's (Nigeria) persistent high level of imports of lime [6]. The importance, cannot be over emphasized as a chunk sum of money is yearly spent on importation of lime to meet its annual demand of about 72,000 tonnes with the market price of about $100.00 per tonne [5]. This is to say that, the draw on foreign reserves for the importation of chemical lime is about $7.2 Million per annum.

Therefore, an efficient kiln can be developed for our limestone ore resource using a systematic consideration of our local limestone quality with a proper design and construction to cut down the huge sum of money yearly spent on our foreign reserves. The thrust of the paper centers on the application of locally sourced components in the design. Limestone constitutes one of the most common industrial solid minerals widely spread on sedimentary basins of Nigeria. It is quarried for the manufacture of cement in several parts of Nigeria. Apart from being used as raw material for the manufacture of cement, the high quality limestone is used for the production of lime known as calcinations process [7]. The chemistry of calcinations are shown by the following equations:

$$CaCO_3 + Heat \xrightarrow{900\,℃} CaO(s) + CO_2 \quad \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots \; 2.1$$

Limestone Quick lime Carbon (II) oxide

$$6CaCO_3 + MgCO_3 + Heat \xrightarrow{1000\,℃} 6CaMgO + 2CO_2 + O_2 \dots\dots\dots\dots \; 2.2$$

Compound lime Carbon (ii) oxide oxygen

$$MgCO_3 + Heat \xrightarrow{900\,℃} MgO + CO_2 \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots \; 2.3$$

$$C + O_2 \longrightarrow CO_2 \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots \; 2.4$$

$$H_2 + O_2 \longrightarrow H_2O \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots \; 2.5$$

$$S + O_2 \longrightarrow SO_2 \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots \; 2.6$$

Literature revealed that in addition to the chemistry of calcinations, the kinetic of the calcinations needs to be studied in order to obtain parameters that could enable proper design of the kiln. Various models have been put forward as resistances to calcinations by various workers [5]. To develop an appropriate calcinations model, requires a critical study of the calcination kinetics in order to obtain the optimum model parameters which include:

i. Diffusion coefficient to determine the rate of transport of the gas of the reaction zone.
ii. Mass transfer coefficient which determines the overall exchange of mass across the layer of active lime under the calcinations condition.
iii. Thermal conductivity which also determines the rate of heat transfer to the reaction zone.

The loss in mass, the pressure of gas in calcinations environment and the temperature of the calcining particle have successively been limited to the above parameters and their measurements [8]. For limestone, simple conservation law shows that the rate of reaction is best described by:

$ŋ = 4\pi r^2 \rho CO_2^{dr/dt}$ ………………………………………………………... 2.7

Where ŋ = rate of decomposition of carbonate sphere

r = radius of reaction front

ρCO_2 =molar density of CO_2

Equation (2.7) suggests that diffusion of CO_2 through the thin layer of active lime to the outer surface has a role in the rate determination. Ahmed, K.S. [9], showed that lime obtained within these conditions is soft burned lime with no more than 2% un-reacted core. Hills [8], also found that the rate at which CO_2 is being transferred from the reaction front to the bulk gas phase around the calcining stone can be represented by:

ŋ = $4 \pi D [P_p – P_g] r_g$

$RT_g \{(1/r^*) – 1 + (D/\alpha r_o)\}$…………………………………………..2.8

Where ŋ = rate of decomposition of carbonate sphere

D = diffusion coefficient of CO_2 through porous lime

P_p = partial pressure of CO_2 at reaction front

P_g = actual partial pressure of CO_2 in gas phase

r = radius of reaction front

R = universal gas constant

T_g = gas temperature

α = mass transfer coefficient

r_o = initial radius of decomposing sphere.

Furthermore, Okai [10] found that the rate of calcining stone can be represented by:

$$\eta = \frac{-d\,[4\pi r_c^3]}{dt[3V\,CaCO_3]} = \frac{4\,\pi r_c^2\,dr_c}{V\,CaCO_3\,dt} \qquad 2.9$$

The right hand side of equation (2.9) can be integrated between r and r* to give

$$\int \frac{4\,\pi r^2_c\,dr_c}{VCaCO_3} = \frac{4\,\pi r^3_0\,r^3}{VCaCO_3},\ r_c = r_o\ r^* \qquad 2.10$$

Where η = rate of decomposition of carbonate sphere

r_c = radius of reaction front

$VCaCO_3$ = molar volume of carbonate sample

r_o = initial radius of decomposing sample

r^* = dimensionless radius.

From the foregoing equations, Hills [8] derived an equation for the time of calcination as

$$t_c = \frac{[1 + 2\gamma/r_o\,\lambda]}{6\,VCaCO_3\,\gamma\,(P_{eq} - P_g)\,RT_g\,r_o^2} \qquad 2.11$$

Where t_c = time for complete calcination at $r^* = 0$

γ = diffusive parameter

r_o = initial radius of decomposing sample

λ = convective parameter

$VCaCO_3$ = molar volume of carbonate sample

P_g = actual partial pressure of CO_2 in gas phase

P_{eq} = partial pressure of CO_2 in equilibrium

R = gas constant

T_g = gas temperature

Literature also revealed that the three essential factors in thermal decomposition of any stony materials are as follows:

i. The stone must be heated to the dissociation temperature.

ii. The minimum temperature (practically a higher temperature) must be maintained for certain duration, (reaction time).

iii. The gas that would be evolved must be rapidly removed.

The above conditions are desirable for lime production because the aim is to produce a completely calcined soft-burned lime with no untreated core or no more than 1-2% un-reacted core. Such lime produced is more porous and chemically reactive. Therefore, the thermal requirements for lime vary greatly between 3.25 x 10^9 J/ton and 10.0 x 10^9 J/ton as a result of contingency upon kiln design, types, physical sizes of stone and particular operating skill.

EXPERIMENTAL

A variety of process, structural and environmental factors influence the choice of material and mechanical design features that can be used in kiln construction. A typical kiln framework is made up of metallic and refractory materials such as steel plate and refractory bricks.

Steel plate is one of the metallic materials used for encasing the outer wall of the kiln in order to reinforce against warping. Other metallic materials used are angular iron, galvanized sheet, galvanized pipes, rods and electrodes.

Refractory materials include bricks, mortars and castables. Refractory bricks are used for lining the interior of furnaces, fireboxes and equipment operated at high temperature. Refractory mortars are heat setting or air setting special cement required to bond the individual refractory bricks together into one solid unit, while castables are high temperature concretes made from graded refractory aggregates bonded with hydraulic setting cements. Other materials and auxiliary equipment used are diatomite as insulating material, water as wetting agent, kerosene as firing fuel, air compressor and blower to supply the secondary air to the burner.

Design of a Vertical Shaft Lime Kiln

Generally, design is a creative activity which puts ideas together to achieve a desired purpose. It could be creation of a new product or process [11]. This design involved the manufacture of a new product that is, processing of limestone to lime using kerosene as the firing fuel. The design was influenced by many factors which include:

Quality and size of limestone, chemical composition and physical structure of limestone, nature of fuel and sulphur content, extent of combustion area and the composition of the gases leaving the kiln. More so, the volume of air admitted, temperature of the several zones within the kiln, flow of gases, the counter-movement of the lime and all other variations influence the design of kiln.

Mass Balance

Basis: 250kg/batch of lime

Limestone: $CaCO_{3(s)}$ + heat $\longrightarrow$ $CaO_{(s)} + CO_{2(g)}$ …………..…………… 3.1

100 56 44

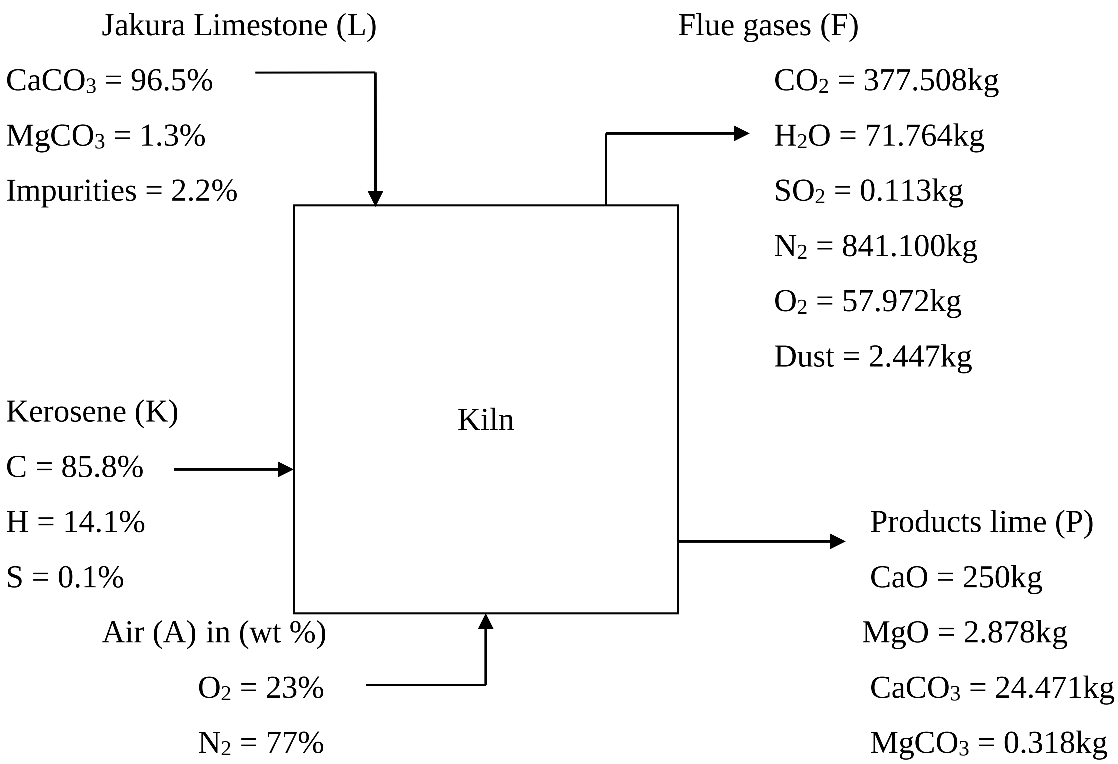

Figure 1: Composition of the materials in and out of the kiln.

Energy Balance

From the simple law of energy conservation, heat input = heat output. Assume limestone is heated to 900^0C, and it is then heated to dissociation completely at 1080^0C. Then heat required to calcine limestone from ambient temperature to the calcination temperature can be computed. Figure 2 summarizes the movement of materials and temperature distribution over the entire kiln. The computation can be shown as below:

$$0.965\int_{303}^{1173}\left(19.68+0.01189T-\frac{307600}{T^2}\right)dT\times\frac{4.2}{100000}$$

$$+0.022\int_{303}^{1173}\left(17.09+0.00045t-\frac{897200}{T}\right)dT\times\frac{4.2}{60000}$$

$$+0.013\int_{303}^{1173}(16.9)dT\times\frac{4.2}{84000} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad 3.2$$

Substituting in the foregoing equation gives:

$$= 0.965\left[19.68(1173-303)+\frac{0.01189}{2}\left(1173^2-303^2\right)+307600\left(\frac{1}{1173}-\frac{1}{303}\right)\right]\times\frac{4.2}{100000}$$

$$+0.022\left[17.09(1173-303)+\frac{0.000454}{2}\left(1173^2-303^2\right)+897200\left(\frac{1}{1173}-\frac{1}{303}\right)\right]\times\frac{4.2}{60000}$$

$$+0.013[16.9(1173-303)]\times\frac{4.2}{84000}$$

= 1.001GJ/ton.

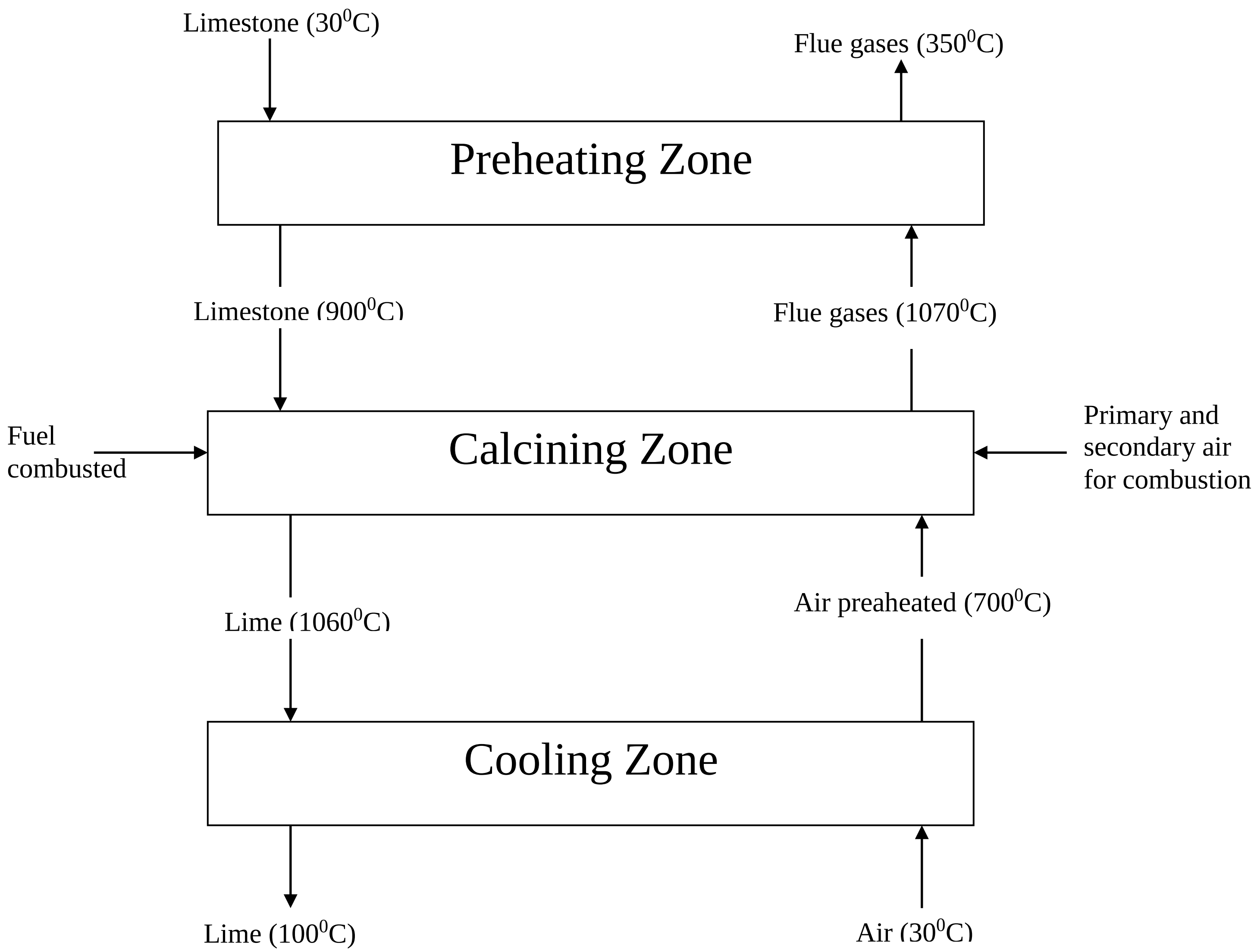

Figure 2: Movement of materials and temperature distribution over the entire kiln

Sizing of the kiln

A typical vertical shaft lime kiln is made up of several imaginary zones with a specific diameter which is a function of its height. Figure 3 shows the dimension of the kiln shaft. The computation for each imaginary zone is shown as below:

Volume of limestone calcined/batch

$$= \frac{489.416}{2713}$$

$= 0.180\ m^3$

If normal voidage for well graded particles in packed beds (fluidized bed) is used e = 37 % [12]

Volume of calcining zone

$$= \frac{0.180}{1-0.37}$$

$= 0.286m^3$

If kiln internal diameter is fixed at 0.6m at calcining zone

$$V = \frac{\pi(0.6)^2}{4} H_c = 0.286$$

$H_C = 1.01m$

Height of calcining zone H_C is approximately 1.00m.

Height of cooling zone, H_{CL}

If volume of calcining zone = $0.286m^3$

Then volume of cooling zone = 0.6 (0.286) = 0.173m3

But the cooling zone is made up of cylindrical and conical parts.

The volume of the conical part is given by

$$V = \frac{\pi D_1^2}{4} H_{CL_2} - \frac{\pi D_2^2}{4} H_{CL_2}$$

Where, D_1 = 0.6m, D_2 = 0.25m & H_{CL_2} = 0.4 m

$$= \frac{\pi(0.4)}{4}\left(0.6^2 - 0.25^2\right)$$

Then volume of conical part = 0.092 m^3

Volume of cylindrical part = 0.173 – 0.092 = 0.081

$$\Rightarrow \frac{\pi(0.6)^2}{4} H_{CL} = 0.081$$

H_{CL} = 0.286 m

Then the height of cooling zone is approximately 0.30 m

$\therefore$ Height of preheating zone = 1.70m

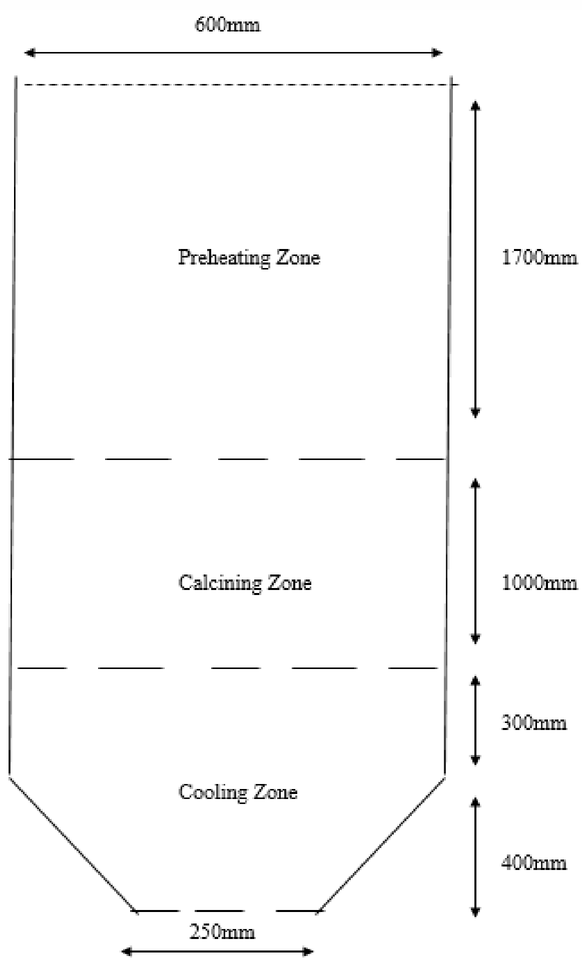

Figure 3: Vertical shaft lime kiln showing imaginary zones and internal diameters

Construction of a Vertical Shaft Lime Kiln

Vertical shaft lime kiln has distinct features with a couple of auxiliary equipment. The various sections that make up the plant include the following: kiln stand, kiln shaft, kiln top cover, chimney with rain cap, burner ports and discharge chute. Figure 4 shows the assemblage of these sections.

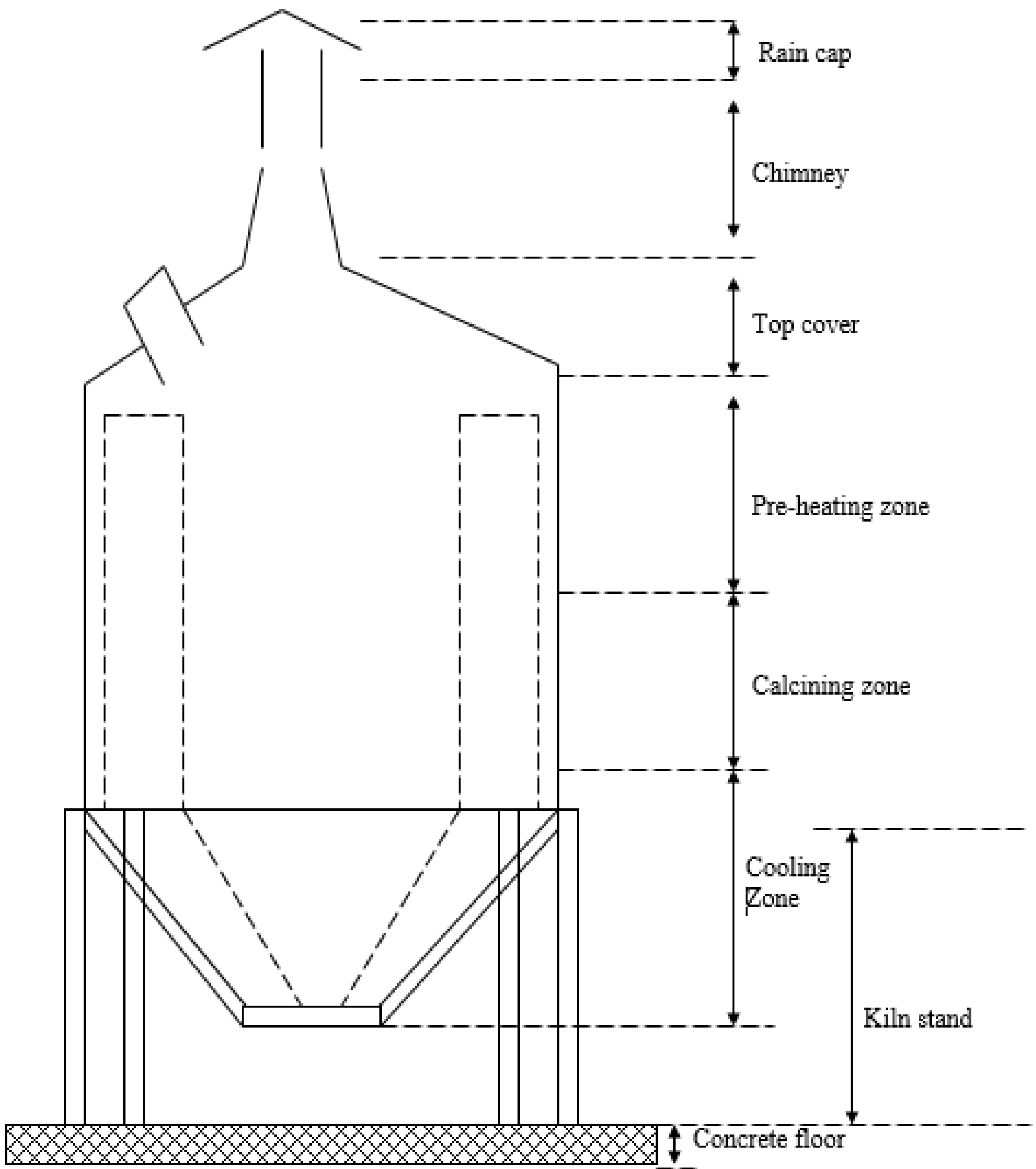

Figure 4: Vertical shaft kiln with distinct features

Figure 5 illustrates the positions of the thermocouple for the temperature profile during the test-running of the kiln.

Scale: 1:200

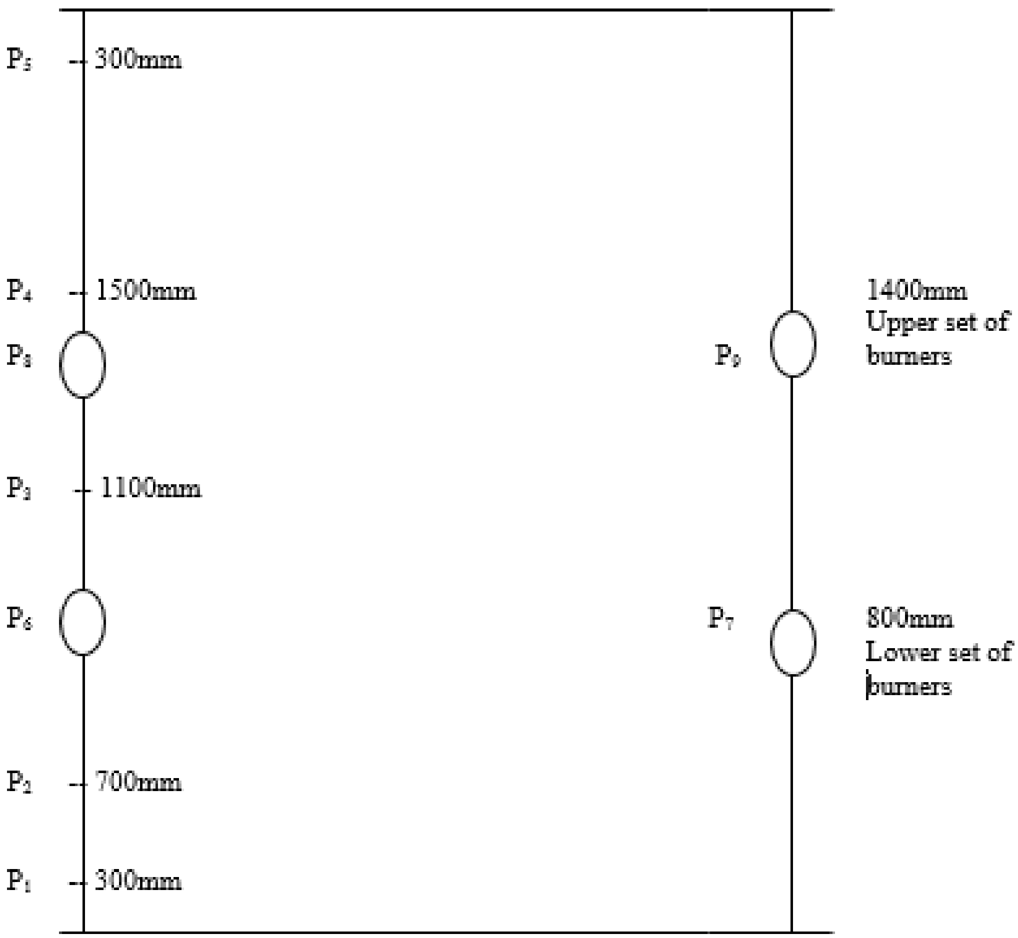

Figure 5: Positions of the thermocouple and burner holes on the kiln shaft.

Test Running of a Vertical Shaft Lime Kiln

This involved the integrity of installation and kiln firing procedure. The plant was properly installed on a heavy steel rod, reinforced concrete to carry the entire load of the kiln, auxiliary equipment and charged limestone; all estimated at 10 tonnes weight in total. All the components of the kiln were properly welded and flanged together with access platform anchored to the kiln structure. The kiln firing also involves start up procedure, system trouble shooting and shut down procedure. Limestone crushed to 5cm in diameter were charged, the pilot flame was then lit and the burner was opened to commence the burning operation. Due to the peculiarities of the local design, there may be upsets during the operation of the system. These include backfiring, channeling, stratification, insufficient burning time and hanging of kiln charge. All these were identified and minimized from the design. Also due to the provision of a stand by generator set. The stabilized condition was indicated with good flame spray of whitish to bluish colour. Then temperature profile test was carried out to determine temperature levels at various positions of the kiln. After two to three hours the kiln was shut down and active lime was collected through the discharge chute for analysis.

RESULTS AND DISCUSSION

The stability and integrity of the plant installation seemed to be good. The thermal efficiency of the kiln was determined by increasing the temperature profile across the kiln shaft with time and specific aggregate size of the limestone.

The peak average gas temperature was about 1200 ℃ which conformed to theoretical presumption. As calcination was in progress for three hours, the lime obtained was pure white, crystalline, faint distinct odour, light and soft, which reacted with water to evolve heat. The pH ranged from 11.0 to 12.5, settling rate was low and available lime was 86 wt%.

CONCLUSION

An improved performance of a vertical shaft lime kiln has been developed to an industrial size. The stability and the integrity of the plant installation were good. There was adequate thermal insulation to maintain low outer temperature. The serious systems troubleshooting, particularly backfiring that is usually encountered in the operations of locally fabricated vertical shaft lime kiln due to poor draft was minimized. The high down time encountered during the charging and discharging of most local kilns was also minimized. The calcined lime obtained competes in quality with the market lime. Therefore, it is recommended for public and private investors.

Furthermore, investments in materials technology worldwide have increased, demanding new tools and equipment. In Nigeria, the innovations have not made any appreciable impacts on the economy because due recognition has not been given by government and industry. This is to say that, increase public and private investments in materials technologies through well directed foresight, that is, exploration of indigenous technology for the local fabrication of plant machinery in material processing is very crucial in Nigeria in order to revive the country's dwindling economy, this would not only discourage the population's habit of "buying and selling" but would encourage a culture of "do it yourself" and reverse the nation's habit of relying on foreign technology and goods because no nation can prevail without indigenous technology.

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