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Investigation of some factors that affect jakura limestone burning

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Limestone calcination reaction seems to be a very simple and straight-forward reaction. However, there are numerous critical variables that exert profound effect on lime burning operations. The factors and variables that affect the burning of limestones must be considered in the selection, design and optimization of the calcininig equipment. Limestone burning in a vertical kiln often presents complex problems which can be solved from the conception by consideration of the prevailing factors that determine the progress of calcinations reactions. The evaluation of the influence of these factors on the progress of the burning of Jakura limestone in a vertical shaft lime kiln is the thrust of this work. Basic kinetic parameters such as: diffusivity, mass transfer coefficient, conductivity, heat transfer coefficient, convective parameter, and diffusive parameter of the lime layer of the calcining limestone particle were obtained from the calcinations tests. Computer programs were developed to evaluate the effects of these factors for typical burning conditions. The shrinking core kinetic model of the reaction limited by heat and mass transfer was employed in the evaluation. The effects of chemical kinetics, stone size and gradation, calcination temperature, calcination time, effect of pressure and flow conditions in the kiln were evaluated.

Key words: Limestone, calcination, vertical shaft lime kiln, shrinking core kinetics, calcining equipment.

INTRODUCTION

Limestone ($CaCO_3$) is an important raw material in many process industries such as: water and waste water treatment, surface coats and paints, petroleum refining, chemical synthesis, fertilizer manufacture etc. It's application most times require that the limestone be calcinated in shaft or rotary kilns, where carbonate is thermally decomposed to produce lime and CO_2. The reaction is endothermic and consists of five process steps: a) heat transfer from ambient to the solid surface, b) heat conduction from surface to the reaction front, c) chemical reaction at the front, d) diffusion of CO_2 through the porous oxide layer to the surface and e) the mass transfer into the surroundings. The heat and mass transfer between fluid and solid have been adequately investigated (Hai and Specht, 2011)

There are numerous critical variables that exert profound effect on lime burning operations. These factors are usually considered in the light of the chemical kinetics and physical transport phenomena that occur in a kiln (Gilchrist 1989). Limestone calcination reaction has many attendant complexities that often pose many problems to successful lime burning operations and these are discussed in the following sections. Jakura Limestone is found in the central region of Nigeria and has been estimated to be over 46million tones reserve (Abdullahi, 1996). This thus has great potentials of contributing to the

Table 1. Chemical composition and physico-technical properties of jakura limestone.

Constituents	Average content of limestone	Average content of lime
LOI (%)	42.66	2.69
SiO_2 (%)	1.84	1.17
Al_2O_3 (%)	0.34	0.42
Fe_2O_3 (%)	0.21	0.14
CaO (%)	54.05	94.79
MgO (%)	0.63	0.84
R_2O_3 (%)	0.02	-
$K_2O + Na_2O$ (%)	0.09	-
P_2O_5 (%)	0.03	-
SO_3 (%)	0.14	0.06
Density (g/cm^3)	2.713	-
Apparent density (g/cm^3)	2.69	-
Water absorption (%)	0.4	-
Open porosity (%)	0.9	-
Compression strength (kN)	33.0	-
Abraidability (%)	16.75	-
Bulk Density (g/cm^3)	1.38	-

Source: Okonkwo (1991).

National Gross Domestic Product (GDP) if well exploited hence the interest in this study.

The physical and chemical characterization of Jakura limestone is in Table 1.

Stone size and gradation

During calcination of limestone, dissociation usually progress gradually from the surface into the interior of the stone. The larger stone sizes are more difficult to calcine and require more time. A wide range of particle size distribution in kiln feed also interferes with heat distribution in the kiln. The small stones accumulate between the voids formed by large stones in shaft kilns, thus impeding the draft and the flow of combustion flame and gases (Wuhrer, 1965). While calcining a wide range of stone sizes, temperatures that calcine the smaller sizes adequately without over burning will only calcine the outer shell of the larger diameter stone. Consequently, restricted gradations of stone, regardless of size are much easier to calcine. The size of the limestone is the most critical element in calcinations. As the limestone enters the kiln, it is exposed to the hot gases within the kiln. The rate of heat penetrationis based on the temperature of the stone and that of the surrounding gases in addition it takes time for heat to penetrate the limestone. The smaller the stone, the shorter the time of heat penetration. In the case of pulverized limestone, this time may be far less than a minute (Fuertes et al., 1993).

Kinetics

The decomposition of limestone is an endothermic topochemical reaction:

$CaCO_3$ + ΔH_R = CaO + CO_2
(solid)   (reaction enthalpy)   (solid) (gaseous)
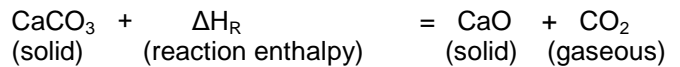
The calcinations process can be explained using a partially decomposed piece of carbonate, whose profiles of CO_2 partial pressure and temperature are shown in Figure 1 which was adapted from the work of Agnieska (2006). The specimen comprises a dense carbonate core surrounded by a porous layer. In the calcinations reactor at a temperature T_{gas} heat is transferred by radiation and convection (symbolized by (α) to the solid surface at a temperature of $T_{surface}$. By means of thermal conduction (λ) heat penetrates through oxide layer to reach the reaction front, where the temperature is T_f. As the reaction enthalpy is many times greater than the internal energy, the heat flowing further into the core is negligible during the reaction. Therefore the core temperature is only slightly lower than the front temperature. Once heat is supplied, the chemical reaction constant (k) then takes place for which the driving force is the deviation of CO_2 partial pressure from the equilibrium (p_{eq}- p_f). The released CO_2 diffuses (D^p) through the porous oxide layer to the surface and finally passes by convection(β) to the surroundings where the CO_2 partial pressure $p_{surface}$ exists.

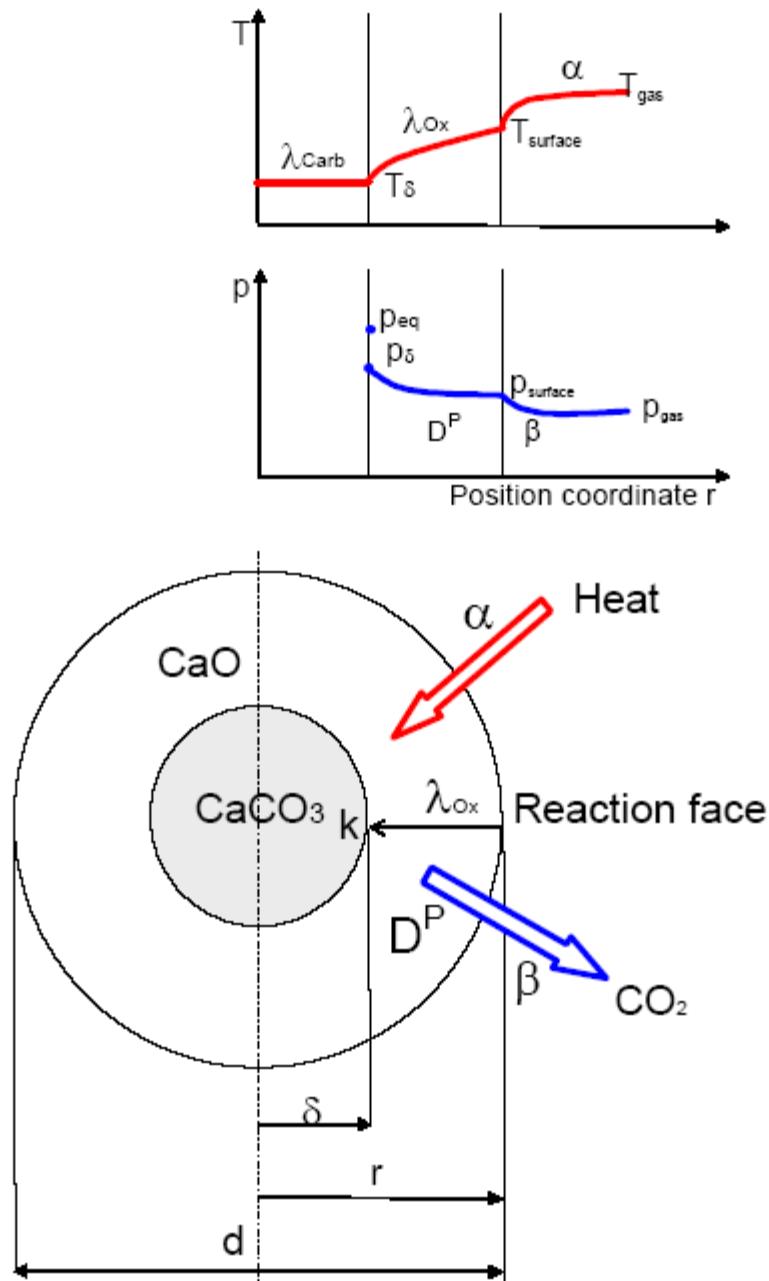The chemical and physical properties of limestone and

Figure 1. Profile of calcining calcium carbonate sample.

the lime such as the conductivity, mass transfer coefficient, diffusivity of the lime layer influence the calcination of the limestone. Hu and Scorani (2003) conducted experiments with pulverized limestone about 60 µm and obtained a reaction coefficient of 0.11 $mol/m^2/s$ and thermal conductivity from 0.10 to 0.86 W/M/K. Borgwardt (1989) measured two types of limestone based on 1 µm powder, and concluded that the reaction rate coefficient at 850°C is 0.012 $mol/m^2/s$. Fuertes et al. (1993) conducted experiments over a size range of 0.25 to 1.85 mm in a fluidized. Their result was 0.077 $mol/m^2/s$ at 850°C. Using a thermogravity metric analyzer under isothermal and non-isothermal conditions. Khinasi (1996) studied the pore diffusivity and the reaction rate by using limestone powders ranging from 5 to 100 µm. Moffat and Wamsley (2006) carried out experiments at temperature range of 850 to 1200°C and limestone particle size 5 to 25 mm. The thermal conductivity lies between 0.1 and 1.5 W/M/K. Under ambient conditions with CO_2 concentration from 0 to 80%

and limestone particle size from 0.4 to 2.0 mm. Fuertes et al. (2002) evaluated the reaction coefficient varying form 0.6 to 3 mol/m^2/s. The properties were however obtained in this study using particle range of 14 to 20 mm radius as these sizes are in the range of particle sizes usually burnt in vertical shaft kilns.

A one dimensional shrinking core model can be established based on the assumptions of ideal geometry such as sphere, cylinder or plate, a homogeneous chemical composition and structure in the sample and structure in the sample, and a symmetrical heat supply. The reaction starts uniformly on the solid surface always forming a smooth reaction front, which then processes continuously into the interior as shown in Figure 1 which was adapted from the work of Agnieska (2006). Based on the shrinking core model, Szekely et al. (1976) and Kainer et al. (1986) have derived a couple of differential equations to calculate the decomposition temperature (T_f) and the conversion degree(X) depending on time t.

Several workers have proposed models for the calcinations of limestone Dennis and Hayhurst (1987) and Moffat and Wamsley (2006) showed that for very small particle diameter of about 0.4 to 2.00 mm and less the reaction is controlled by chemical reaction resistance and Hills (1968) conclusively proved that for larger particle diameter of about 10 mm and greater the calcination reaction is controlled by heat and mass transfer across the lime layer surrounding the calcining particle. The following equations thus describe the progress of the reaction of large paricles; the rate of reaction is described by Equations 1 and 2.

$$\acute{n} = 4\pi r^3 \rho_{co2}\ \frac{dr}{dt} \tag{1}$$

Where: $\acute{n}$ = rate of decomposition of carbonate sphere(mols/s), ρ_{CO2} =molar density of carbon dioxide (mol/m^3), r = radius of the reaction front (m).

$$\acute{n} = \frac{4\pi r D\{P_R - P\} r}{R'\theta_R T\{(\frac{1}{r*}) - 1 + (D/\alpha r_0)\}} \tag{2}$$

Where: D = diffusion coefficient of CO_2 through porous lime(m^2/s × 10^{-4}), P_R = partial pressure of CO_2 at the reaction front of decomposing particle(atm), P=partial pressure of CO_2 in bulk gas surrounding the decomposing particle(atm), θ_R = temperature of reaction front(K), T =temperature of bulk gas surrounding the decomposing particle(K), α = mass transfer coefficient to surface of carbonate sample(m/s ×10^{-1}).

The weight loss as the calcination progresses is related to the radius of the calcining particle as in Equation 3.

$$r* = r_c/r_{o=}\ (m*)^{1/3} \tag{3}$$

Where: r*= dimensionless radius, r_C = radius of the core

of the decomposing particle(cm), r_o = initial radius of the decomposing particle(cm), m* = dimensionless mass of the decomposing particle.

The rate of heat transfer to the reaction front is given by Equation 4.

$$q = \frac{4\pi k(\theta_{p-}\theta_G)r_o}{(1/r*) - 1 + (k/hr_o^2)} \tag{4}$$

Where: k = thermal conductivity of porous lime layer(Jm^{-1}s^{-1}C^{-1}), θ_P =temperature of reaction front(K), θ_G =temperature of the bulk gas surrounding the decomposing particle, h =heat transfer coefficient between the particle outer surface and the surrounding (Jm^{-1}s^{-1}C^{-1}).

The time for complete reaction of a calcining particle is given by Equation 5.

$$t_c = \frac{[1 + 2\Gamma/r_o\Lambda]}{[6V(P_{eq} - P)/RTr_o^2]} \tag{5}$$

Where: t_C = time for complete calcinations (min), Γ =convective parameter, Λ =diffusive parameter, R =gas constant in mechanical units (cm^3 at mgmole), T =temperature of bulk gas surrounding the decomposing particle (K), V= volume of particle (m^3), P =partial pressure of bulk gas surrounding the decomposing particle, P_{eq} =partial pressure of CO_2 in equilibrium with lime and calcium carbonate at the temperature of the furnace gases (atm).

Calcination temperature

The dissociation temperatures of calcite and magnesium carbonate at 1 atm and 100% CO_2 atmosphere are 898°C and 402 to 480°C respectively (Takkien et al., 2012). Dissociation always proceed gradually from the outside surface inward. For dissociation to penetrate the interior of the limestone, higher temperatures are necessary and must be further elevated for dissociation to occur in the centre of the stone (in practice generally well in excess of the preceeding dissociation points) (Lu et al., 2009). The higher the diameter of the stone, the higher the temperatures required for the dissociation of the core due to increasing internal pressure as the CO_2 gas forces it-s escape. An increase in temperature exerts a much greater influence on the dissociation rate than temperature retention.

Time of calcination

It has been found out that regardless of the type or quality of limestone a higher burning temperature and

longer calcination period produces a harder-burned quicklime that has high shrinkage, high density, low porosity and low chemical reactivity. The converse prevails at lower burning temperatures with shorter burning duration yielding the desirable, soft-burned highly reactive limes of low shrinkage and density and high porosity (Keiner et al., 1986). The calcining effort of small and large stones in terms of their relative heating and calcination times is directly proportional to the square of the thickness (or average diameter for irregularly shaped stone (Boynton, 1980). Retention time depends on the size of the limestone as well as calcinations temperature. If the retention is too short, the core of the limestone will remain calcium carbonate while the outside will convert to calcium oxide. If the retention time is too long, the surface of the pebble will shrink and the pores created by CO_2 gas escape will close, producing an impervious surface (Wei et al 2010). This type of lime is called hard burned or dead burned lime. This lime will not slake in standard slakers. In addition, longer retention time means less production and higher costs for manufacturing.

Chemical reactivity

The factors of porosity, density and pore size distribution are interrelated and exert a profound influence on such standard measurable properties of quicklime as reactivity, available lime and the particle size distribution and the surface area of the resulting hydrated lime, it has been found out that a retention time of 1 to 4 h had little or no effect on porosity, surface area, or reactivity at mild calcination temperatures of 954 to 1066°C and the bulk density remain constant. Excessive calcination temperatures and prolonged periods of calcinations lead to hard burning of limestone and this produces generally unreactive limes.

Shrinking characteristics

The shrinkage of quicklime can be calculated from the bulk specific gravity of the limestones and allowing for the loss on ignition by the formular (Boynton, 1980).

$$S = 100 \times \frac{\frac{100}{D_S} - \frac{100 - L}{D_L}}{100 D_S} \tag{6}$$

Where: $S_L=$ Shrinkage (%), $D_S =$ Bulk density of stone (g/cm^3), $D_L =$ Bulk density of quicklime (g/cm^3), $L_f=$ Loss of ignition of stone %.

Shrinkage of the limestone has profound influence on the bulk density of the limestone charge in the kiln. The higher the shrinkage the less the voidage of the packing and this can lead high pressure drop in the kiln bed with the attendant influence on the draft of flue gases from the kiln (Borke et al., 2008).

Quality and type of fuel

The quality and type of fuel exerts a profound effect on the efficiency of the kiln and the quality of lime produced. Crude fuels as wood and coal have been employed from time immemorial. Pulverized coal, producer gas, natural gas and oil are also employed. Natural gas is the most convenient fuel and producer gas is the most troublesome. The final choice of fuel is also determined by environmental considerations since some fuels have more tendency to pollute the environment through deleterious emissions.

Typically, vertical kilns use oil or natural gas for fuel, where as horizontal kilns use coal. However, either type of kiln can use any of these fuels. Both oil and coal contain certain percentages of sulphur compounds. These vary from 0.5 to 3%. Sulphur will combine with CaO at proper temperatures and produce calcium sulphide or calcium sulphate. This generally happens on the surface of CaO pebbles and renders them non porous, thus not suitable for slaking. In addition, a high percentage of ash in the coal will result in build up on the refractories in the rotary kiln, thus interfering with the flow of limestone in the kiln. The kiln must be periodically cooled and the ash build up removed manually which is a very costly operation. Natural gas is the cleanest fuel and mostly used in vertical kilns. To calcine limestone for food grade lime, natural gas is the fuel of choice. Typical quality parameters of the main fuels employed are shown in Tables 2 and 3 (Agnieska, 2006).

MATERIALS AND METHODS

Calcination test

A laboratory muffle furnace of internal dimension of 30 by 20 cm manufactured by Philip Harris UK was used. The furnace is electrically heated and is furnished with temperature regulator thermostatically controlled and has a temperature rating of up to 1300°C. The temperatures used in the study are usually set and sized limestones are burned in very clean nickel crucibles. The' weight of the samples are monitored over the periods of calcination. The weights are measured with electronic analytical balance to 0.01 g. This is by withdrawing the sample from the furnace at intervals and taking the weight. The measurement is done very fast manner at intervals of five minutes. This is to ensure that the sample readily assumes the temperature of the furnace. The opening of the furnace door at intervals ensures the sweeping of air through the furnace to keep the composition of the gas phase around the sample fairly constant during each run. The rate of reaction was obtained by numerical differentiation of the sample weight using Lagrange's five point interpolation formula. The sized samples are assumed to be spherical since all previous works have used spherical samples or samples are treated as if they are spherical. This is in consonance with previous work (Hills, 1968). The basic data obtained from this test were the reaction rate and weight loss.

Table 2. Composition, air demand and net calorific value of the gaseous fuels.

Fuel	CH_4	C_2H_6	H_2	CO_2	CO	N_2	L1 (m^3_{air}/m^3_{fuel})	L2 (kg_{air}/kg_{fuel})	Calorific value h_v (MJ/kg)
Weak gas	-	-	0.02	0.16	0.66	0.16	1.64	2.44	6.6
Natural gas I	0.82	0.03	-	0.01	-	0.14	9.1	15.1	38.3
Natural gas H	0.93	0.05	-	0.01	-	0.01	9.69	15.84	47.3

Source: Agnieska (2006).

Table 3. Composition (dry and ash free), air demand and net calorific value of solid fuels.

Fuel	C	H	O	S	N	L (Kg_{air}/kg_{fuel})	Calorific value h_v (MJ/kg)
Anthracite	0.92	0.04	0.02	0.01	0.01	12	32.8
Lignite	0.7	0.05	0.25	-	-	7.3	20
Coke	0.98	-	-	0.01	0.01	12	28.7

Source: Agnieska (2006).

The reaction was carried out at atmospheric pressure. The basic data were employed in the reaction model equations to carry out plots from where the kinetic parameters were determined from. The details of this procedure are as in the previous works (Hills, 1968).

Evaluation of factors affecting calcination

The reaction mechanism model was solved using Microsoft Fortran Software programme developed. A range of typical calcinations conditions were used as input in the computer programmes to determine the effects on the progress of the reaction. The programs can be obtained on request from the author. The kinetic parameters namely; thermal conductivity, diffusivity, mass transfer coefficient, convective parameter and diffusive parameter obtained from the calcination test were used as basic as part of the input data in the heat and mass transfer limited reaction model.

RESULTS AND DISCUSSION

Effect of limestone particle size

Tables 4, 5 and 6 show the variation of reaction time with dimensionless radius of the limestone for various stone sizes. The dimensionless radius is the ratio of the radius of the uncalcined section to the radius of the whole particle. The dimensionless radius as a study parameter is a measure of the core of the limestone particle which is yet to be calcined. From the tables, it can be shown that the calcinations time increases with stone size. Also for a particular size of stone, the time of calcinations increases as the dimensionless radius increases. The increase in dimensionless radius depicts decrease in penetration of the core of the stone. From Figure 1 earlier presented it can be seen that the reaction progresses from the outer surface of the calcining particle into the inner part of the particle and that the lime layer builds around the uncalcined core of the particle hence dimensionless radius gives the extent of the penetration of the core of

the particle. The particle is completely calcined when the dimensionless radius is zero. Tables 7 and 8 shows the variation of core penetration rate with pressure gradient across a reacting limitation particle and reaction rate with dimensionless radius.

As the calcinations progresses the CO_2 that is formed at the reaction front of the remaining core is expelled to the outer surface through the lime layer. For the gas to be readily expelled without a build up at the reaction interface there is need to have sufficient internal pressure gradient across the particle to ensure that the CO_2 formed do not build at the interface as this can promote the backward reaction which is reformation of calcium carbonate since the decomposition of calcium carbonate is an equilibrium reaction (Khinast et al., 1996). The larger the size of the calcining particle the larger the internal pressure gradient that must exist to sufficiently expel the formed CO_2 without favouring the backward reaction. This explains the trend shown in Table 7. Larger particle sizes will require faster rate of decomposition to achieve same level of conversion as will be required by smaller particle sizes. This explains the trend shown in Table 8. The rate of calcination and rate of expulsion of formed CO_2 can be increased by calcining at more stringent temperature conditions(Kilic and Aril, 2006).

Effect of calcination temperature and pressure

The times for complete calcinations of limestone of selected sizes at selected temperatures and surrounding bulk gas pressure representing the internal pressure of the kiln are shown in Tables 9 and 10. From the Tables 9, 10, and Figures 2 and 3, particles of same size burned at different temperatures have different times of complete calcination. The time of complete calcinations decreases with increase in temperature, but exhibits characteristic

Table 4. Variation of complete reaction time with dimensionless radius (Diffusion through product layer limited reaction for invariant particle size).

Dimensionless radius	Complete reaction times (s)/Particle radius (m)		
	0.025	0.04	0.05
0.10	7.88E+03	2.01E+04	3.15E+04
0.15	7.62E+03	1.95E+04	3.05E+04
0.20	7.27E+03	1.86E+04	2.91E+04
0.25	6.84E+03	1.75E+04	2.74E+04
0.30	6.36E+03	1.63E+04	2.54EE+04
0.35	5.83E+03	1.49E+03	2.33E+04
0.40	5.26E+03	1.35E+03	2.10E+04
0.45	4.66E+03	1.19E+03	1.86E+04
0.50	4.06E+03	1.04E+03	1.62E+04
0.55	3.45E+03	8.83E+03	1.38E+04
0.60	2.86E+03	7.31E+03	1.14E+04
0.65	2.29E+02	5.85E+03	9.14E+04
0.70	1.75E+02	3.24E+02	7.0E+03
0.75	1.27E+-2	3.24E+02	5.05E+03
0.80	8.43E+02	2.16E+02	3.37E+02
0.85	4.92E+02	1.26E+02	1.97E+02
0.90	2.27E+02	5.81E+02	9.08E+02
0.95	5.8E+01	1.50E+01	2.35E+02
1.0	0.0	0.0	0.0

Table 5. Variation of the calcination time with particle radius and dimensionless radius (Diffusion through product layer limited reaction for variant particle size).

Dimensionless radius	Complete reaction times (s)/Particle radius (m)		
	0.025	0.04	0.05
0.10	3.54E+03	5.67E+03	7.09E+03
0.20	3.52E+03	5.64E+03	7.04E+03
0.30	3.45E+03	5.53E+03	6.91E+03
0.40	3.32E+03	5.32E+03	0.65E+03
0.50	3.11E+03	4.97E+03	6.21E+03
0.60	2.78E+03	4.45E+03	5.57E+03
0.70	2.33E+03	3.73E+03	4.67E+03
0.80	1.73E+03	2.77E+03	3.47E+03
0.90	9.62E+02	1.54E+03	1.92E+03
1.0	0.0	0.0	0.0

lower calcinations time at 1060°C. The main trend of the decrease in calcinations time with increase in temperature is in agreement with Moffat and Wamsely (2006) however, the low calcinations time observed for the temperature 1060°C suggest an optimal because the low calcinations imply lower calcinations effort needed in terms of energy input within the range of the calcinations temperatures. It was also observed that the calcinations times increased with increase in partial pressure of CO_2 in the bulk gas surrounding the calcining particle. This is also in agreement with literature (Dennis and Hayhurst, 1987). It has also been shown that the decomposition of calcium carbonate is an equilibrium reaction and that the increase in partial pressure of CO_2 favour the backward reaction which implies recarbonation of the decomposing particle. This necessarily slows down the reaction.

Limestone quality

From Table 1 it can be seen that Jakura limestone is a

Table 6. Variation of complete reaction time with dimensionless radius (combined resistances limited reaction).

Dimensionless radius	Complete reaction times (s)/Particle radius (m)		
	0.025	0.04	0.05
0.10	1.95E+04	4.62E+04	7.04E+04
0.20	1.82E+04	4.30E+04	6.54E+04
0.30	1.63E+04	3.83E+04	5.79E+04
0.40	1.39E+04	3.24E+04	4.88E+04
0.50	1.12E+04	2.59E+04	3.88E+04
0.60	8.55E+03	1.92E+04	2.85E+04
0.70	5.88E+04	1.28E+04	1.87E+04
0.80	3.45E+04	7.14E+04	1.02E+04
0.90	1.43E+03	2.73E+03	3.77E+03
1.0	0.0	0.0	0.0

Table 7. Variation of core penetration rate with pressure gradient across product layer (Heat and mass transfer limited reaction).

Pressure gradient(atm)	Complete reaction times (s)/Particle radius (m)		
	Radius=0.025 m	Radius= 0.04 m	Radius =0.05 m
0.1	1.27	2.04	2.55
0.3	3.82	6.12	7.65
0.5	6.38	10.21	12.75
0.7	3.93	14.21	17.86
0.9	11.48	18.37	22.96
1.1	14.04	22.45	28.06
1.3	16.58	26.53	33.16
1.5	19.14	30.62	38.27
1.7	21.69	34.70	43.37
1.9	24.24	38.78	48.47

Table 8. Variation of reaction rate with dimensionless radius (heat and mass transfer limited reaction).

Dimensionless radius	Reaction rate(mols) / particle radius (m)		
	Radius=0.025 m	Radius= 0.04 m	Radius= 0.05 m
0.1	0.74	1.19	1.48
0.2	1.67	2.68	3.35
0.3	2.87	4.59	3.74
0.4	4.46	1.59	3.93
0.5	6.70	7.15	13.40
0.6	10.05	10.72	20.09
0.7	15.63	16.08	31.26
0.8	26.79	25.01	53.58
0.9	60.27	42.86	120.47

high cacium limestone with impurities less than 4%. Jakura limestone when properly calcined will produce a high grade calcium oxide which can be employed in chemical synthesis and also a reactive lime will be obtained often when it is soft burned. With impurities in the stone, calcinations at low temperatures of 899 to 927°C, relatively little silica and other impurities combine with the lime (Boynton, 1980). As the temperature increases, the

Table 9. Times for complete calcination of Jakura Limestone of various particle sizes at various temperatures of calcinations at kiln pressure of -345 mmH$_2$O.

Temp (°C)	Radius(cm)/Times(s)								
	0.4	0.6	0.8	1.0	1.2	1.4	1.6	2.0	2.2
900	4328	7074	10199.2	13708.4	17600	21877.1	26538.2	36961.8	42820.4
960	939.4	1220.1	2636.96	3781.5	5121.1	6654.6	8382.2	12419.6	1420.4
1000	275	619	1027.2	1536	2146.2	2855	3664	5592	6705
1060	149.3	265.1	408.2	578.86	776.3	1001	1254.1	1604.1	2175.2
1080	2133	4742.8	8380.9	13047.6	18738	25452.4	33321.4	51809.5	62238.1

Table 10. Times for complete calcinations of Jakura Limestone of various particle sizes at various temperatures of calcinations at kiln pressure of -100 mmH$_2$O.

Temp (°C)	Radius(cm)/Times(s)								
	0.4	0.6	0.8	1.0	1.2	1.4	1.6	2.0	2.2
900	4461.6	7285.1	10503.8	14117.7	18126.7	22530.8	27330	38114.2	44099
960	939.3	2050	2663.2	3819.4	5171.8	6720.4	8465.2	12543	14876.5
1000	312.86	620.8	1030.1	1491.9	2151.2	2864.2	3677.2	5608.1	6724.9
1060	149.6	265.5	408.7	579.4	777.2	1002.8	1255.6	1605.7	2176.3
1080	2136	4748.6	8390.9	13062.9	18764.7	25496.2	3325.7	5186.9	6221.5
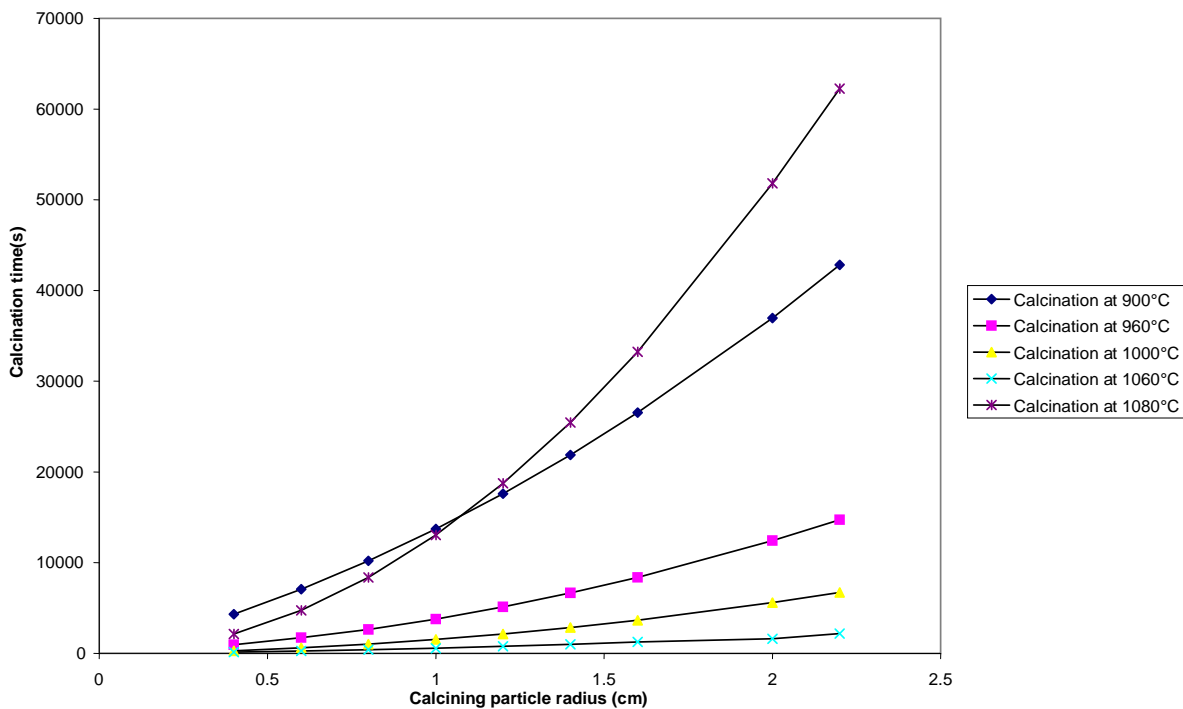
Figure 2. Variation of calcination time with particle radius at -345 mmH20 (Jakura limestone).

uncombined acid oxide impurities are increasingly absorbed. They form various complex calcium compounds such as monocalciun and dicalciurn silicates, calcium aluminates and dicalcium ferrite. Some limestone types cannot be successfully calcined into lump or pebble quicklime. These types dissociate into oxide, but they decrepitate into small fractions and dust, rendering the product unsalable for many uses and also complicate the
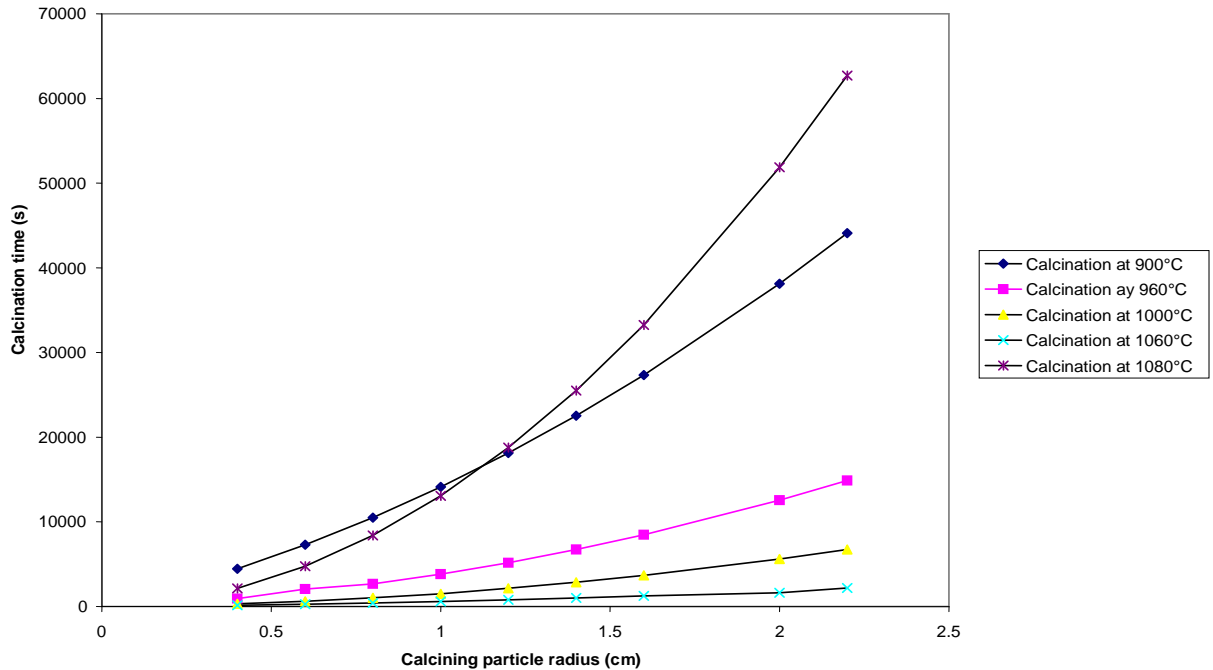
Figure 3. Variation of calcination time with particle radius at -100 mmH$_2$0 (Jakura limestone).

calcination process (Almerinda 1998).. However, Jakura limestone is a high calcium type (CaO content of 95% and above) with low levels of impurities as can be seen in Table 1 hence the lime quality is essentially very good and can be employed as chemical lime in applications.

Conclusion

This work has established the effects of various process factors which prevail during the burning of Jakura limestone in a vertical shaft lime kiln. The factors considered include limestone quality, stone size and gradation, reaction kinetics, calcinations temperature and calcinations time. The trend of the results agree with Kilic and Aril (2006). Calcination temperature of 1060°C exhibits an optimal condition because it implies higher throughput of the calcining equipment and less energy consumption. These trends are very useful in the development of a dynamic kiln model for the burning of a selected limestone. The computer software developed is flexible and can accommodate other limestone sources based on their characteristics and as such can be adopted in development of kilns for such limestone resources. The present work is very fundamental towards sustaining a viable lime production industry in developing nations such as Nigeria.

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