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Fundamental Approach To the Design of Single Vertical Shaft Lime Kiln

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Abstract

A single vertical shaft lime kiln was modeled, designed and operated based on the phenomena controlling the calcinations reaction of a limestone source (Jakura limestone found in Nigeria). The kiln showed a thermal efficiency of 61% and calcinations efficiency of 83%. The results agreed well with the prediction of the calcinations model.

1 Introduction

Lime is the high temperature product of the calcinations of limestone.
Lime is manufacture in various types of kiln by one of the following reactions;

$CaCO_3$ + heat $\longrightarrow$ CO_2 + CaO (high calcium lime)
$CaCO_3.MgCO_3$ + heat $\longrightarrow$ $2CO_2$ + CaO.MgO (dolomite)

The heart of a lime plant is the kiln. There are various types of kiln. The two main types that are commonly employed are the vertical shaft and rotary kilns.

Limestone is one of the oldest industrial materials produced by man. Quicklime was produced in U.S. as early as 1635 in Rhode Island [1]. Today lime continues to be one of the basic supporting materials in the world economy. The fields of water treatment; construction industry, steel production paper manufacture, fertilizer manufacture, etc, all have in common the usage of lime [2].

The world economy as a whole and that of each and every country progressing normally will need more and more lime produced it possible at lower cost and higher quality .Basically lime is produced by two methods, namely; vertical shaft kilns and rotary kilns. Other varieties of kilns have been reviewed [3] .

Each method has its merits and demerits. The merits of vertical shaft kiln include:

(a) Simplicity of construction and operation
(b) Low initial cost
(c) High thermal efficiency
(d) High volumetric efficiency
(e) Minimum decrepitation of solid products and minimum erosion of refractory linings due to slight movement of particles relative to each other.

Careful consideration of these factors indicates that vertical shaft kilns can be installed for about one-half the cost of operated at about two-thirds of the cost of rotary kiln equipment [4],. The major demerits of vertical shaft kiln are higher labour costs and low capacities. However considering the recent development in vertical shaft kilns [5], Predescu [6]) these demerits are no longer arguments against vertical shaft kilns.

Classical kiln, among others, are contingent on process requirements such as capacity, the properties of the limestone and limestone calcinations mechanism. The mechanism determines the calcinations model employed in the design of the kiln. Until recently, kiln know-how has been largely empirical.

In this work a fundamental approach to the vertical shaft lime kiln design based on the phenomena controlling the limestone calcinations reaction was employed. This method has proven to be attractive due to its close prediction of actual operating conditions.

2 Kiln Model

The kiln is modeled on the basis of the process phenomena that limit the calcinations reaction.

From investigations [7], Dennis and Hayhurst [8], and [3] limestone calcinations is limited by heat transfer from the surface of the particle to the reaction front and mass transfer out of the reaction zone (interface).

Assumptions

1. The chemical reaction is rapid, thus the partial pressure of CO_2 at the reaction front is assumed to be the equilibrium value at the temperature there (Tr).
2. There is steady-state (i.e. no accumulation of CO_2 in the newly formed pores in the calcined lime).
3. The CO_2 pressure at the reaction interface is a linear function of temperature.
4. The thermal mass of the sphere is ignored so that all the heat transferred to the reaction front is absorbed by the reaction.

The equation for heat transfer to the reaction interface of a calcining particle in a vertical kiln is given by (Hills 1968).

$$q = \frac{4\pi Kro^{*}Tr - T)}{(1/r^{*} - 1 + K/hro} \qquad (1)$$

$$q = -Hn \qquad (2)$$

Where
q = heat transfer rate to the decomposing sample.
k = thermal conductivity of calcined lime
T_r = temperature at the reaction interface
r* = fractional radius of reaction front
h = heat transfer coefficient between the outer surface of carbonate sample and the surrounding
r_0 = initial radius of carbonate particle
H = moalr heat of decomposition of calcium carbonate
T = Temperature of bulk gas phase

The rate of calcinations is given by (Hills 1968). [7] :

$$q = \frac{4\pi D r_0 (P_r - P_p)}{[(R'T(1/r^{*} - 1 + D/Kgr_o)]} \qquad (3)$$

Where:
n = rate of decomposition of carbonate
D = difussivity of CO_2 in the calcined lime
Pr = partial pressure of CO_2 at the reaction front
Pp = Partial pressure of CO_2 in the calcining particle surrounding.
K_g = mass transfer coefficient to the surface of carbonate sample.

Based on the continuity equation, n may also be expressed as:

$$n = \frac{d}{dt}\left(\frac{4\pi r^{3}_{c}}{3V}\right) \qquad (4)$$

Where r_c = radius of $CaCO_3$ – interface
V = molar volume of calcium carbonate equations (1) to (4) were used by [7] to obtain the relationship for the time for complete calcinations of a particle i.e when ***r**** = 0 as; where

$$t_c = \frac{[1 + 2P/r_0\Lambda]}{[6TP(Y_{eq} - Y_p)/(R'Tr^{2}0)} \qquad (5)$$

where

tc = time for complete calcinations of a carbonate sample
Γ = diffusive parameter
Λ = convective parameter
P = total pressure
Yeq = equilibrium mole fraction of CO_2 at reaction interface.
Yp = Mole fraction CO_2 in the bulk gas phase

The diffusive and convective parameters are defined as;

$$\frac{1}{\Gamma} = \frac{1}{D} + \frac{P_{eq}H^2}{R'R''T^3K} \qquad (6)$$

$$\frac{1}{\Lambda} = \frac{1}{Kg} + \frac{P_{eq}H^2}{R'R''T^3h} \qquad (7)$$

Where
R' = universal gas constant in mechanical units cm^3 atm $gmol^{-1}$ K^{-1}
R'' = universal gas constant in heat units cal $gmole^{-1}K^{-1}$

Assumption

1. The temperature difference between the reaction front and the gas phase is small (the temperature of the reaction front is approximately equal to that of gas phase around the sample.
2. The CO_2 pressure at the reaction front is equal to the equilibrium pressure of the decomposition reaction at the gas phase temperature.
3. The calcinations is carried out in a stationary bed.
4. The calcining particle is spherical.

Equations (1) to (5) relate:

1. The calcinations temperature and time for complete calcinations.
2. The heat transfer to the reaction interface.
3. The system pressure, partial pressure of CO_2 and the rate of calcinations and hence the time for complete calciantion of a particle.
4. The particle size and the rate of calcinations.
5. The transport parameters and the time of complete calcination.

The values of the transport properties, diffusivity, conductivity, mass transfer coefficient and heat transfer coefficient of active lime layer, diffusive parameter and convective parameter obtained from earlier investigations [3], and [9]) on Jakura limestone calcinations were used to simulate the above model. This was to obtain the variation of calcinations time (tc) for a range of particle sizes and system pressure. These data are presented in Tables 1 and 2

Table 1 . Determined Values of Diffusive and Convective Parameters of Jakura Lime

Temperature ^oC	Diffusive Parameter Γ	Convective Parameter Λ
900	0.148	0.175
960	0.094	0.368
1000	0.105	1.080
1060	0.266	0.572
1080	$4.66x10^{-3}$	0.568

Table 2 Computed Results for Complete Calcination of Jakura Marble of Various Particle Sizes at Various Temperature of Calcination at Kiln Pressure of -100mmH_2O

Temperature	Radius (cm)/ Time(s)								
Temp. °C	0.4	0.6	0.8	1.0	1.2	1.4	1.6	2.0	2.2
900	4461.6	2285.1	10503.8	14117.7	18126.7	22530.8	27380	38114.2	44099
960	939.3	2050	2663.2	3819.4	5171.8	6720.4	8465.2	12543	14876.5
1000	312.86	620.9	1030.1	1491.9	2151.7	2864.2	3677.7	5608.1	6724.9
1060	149.6	265.5	408.7	579.4	777.4	1002.8	1255.6	1605.7	2176.3
1080	2136	4748.6	8390.9	13062.9	18764.7	25496.2	3325.7	5186.9	6271.5

The simulation results were used to size the burning zone . The time for complete calcination of the kiln charge size represents minimum residence time of the reacting particle in the burning zone where the decomposition reaction takes place. The preheating zones are sized on the basis of heat transfer from the hot gases from the burning zone , this zone is sized to ensure maximum recuperation of heat from the hot gases.

Kiln performance is determined based on three types of efficiency estimates namely.

1. Thermal efficiency, which is given by heat extracted/Heat fired.
2. Calcination efficiency
3. Overall kiln efficiency, which is given by

$$\frac{\text{Theoretical heat required available oxide}}{\text{Total heat required}}$$

3 Experimental

3.1 Kiln Design Features

The capacity of the kiln is 200kg/D. The kiln had a twin burner system and was fired with LPG(liquefied petroleum gas).

The draft fan had a capacity to create a negative pressure in the kiln to the range of 33.8mbar. The internal refractory fabrication provided a taper fro reduction in diameter from the preheating zone to the burning zone. This was to minimize erosion of the lining normally encountered at jutting ends. The refractory cast was rammed properly to ensure the desired density of the lining to prevent abrasive loss and ensure stability at operating temperature. In order to ensure good energy conservation, the preheating zone was sized to provide a good heat exchange bed to recoup heat from the hot exhaust escaping from the burning zone, also the flow of air through the discharge door into the kiln helped to recoup heat from burnt lime. The exhaust gas temperature was in the range of 38 – 44^0c. he size of the various zones of the kiln are given in Table 3 .

Table 3: Size of kiln zones

Zones	**Parameters**			
	t_k	**H_k**	**Di**	**V_k m^3**
Preheating zone	0.14m	0.81m	0.20m	25.4×10^{-3}
Upper burning zone	0.16m	0.1m	0.18m	2.54×10^{-3}
Lower burning zone	0.19m	0.09n	0.15m	1.59×10^{-3}
Finishing zone	0.19m	0.12m	0.15m	2.12×10^{-3}
Cooling zone	0.19m	0.30m	0.15	5.3×10^{-3}

Legend:
t_k = thickness of lining
H_k = height of zone
D_k = diameter of zone
V_k = volume of zone

3.2 Kiln Productivity

A feed (Jakura limestone) of particle gradation of 4mm to 14mm radius were calcined. The kiln was operated for specified periods while fairly maintaining the desired temperature levels in the burning zone. The calcined limestones were analysed for percent free lime to total lime and conversion. The values obtained represent average values for the range of stone sizes calcined as shown in Table 4.

Table 4 Calcination Results

Time (mins)	Free Lime%	Total Lime%	Conversion%
5	3.36	39	8.5
10	7.16	62.3	11.5
15	59.0	76.6	78
20	61.0	77	79
25	64.5	77.3	83.4

3.3 Kiln temperature profile

The draft fan was started, the burners were started with gas delivered adjusted to 1.4kg/hr flowrate for each burner. 10 selected positions along the kiln shaft measured from the bottom were connected with chromel-Alumel thermocouple to a 27 channel digital temperature readout panel manufactured by Texas instrument. The variation of temperature of the various zones were monitored over time simultaneously. The temperature profiles of the kiln is shown in Figures 1 and 2

3.4 Estimation of CaO and conversion

The consumption of concentrated hydrochloric acid was used to determine the free lime, total lime in the calcined sample and the degree of conversion . Here 4MHcl was used to titrate against a solution of 100 mesh size lime sample the detailed procedure has been presented in literature [2] and [3].

Free lime which was determined by the first stage of the titration represented the actual amount of reactive calcium oxide present. The total lime which was determined by the second stage of the titration presented the total amount of converted limestone. The results are shown in Table 4.

4 Discussion of Results

The kiln temperature profile taken from the 10 positions along the kiln shaft covering the main zones of the kiln are shown in Figures 1 and 2 . Figure 2 shows the temperature profile when the system is operated on half draft. Table 1 shows the temperature profile at full system draft. The draft levels were achieved by careful adjustment of the primary and secondary dampers. The lower burring zone reached a temperature of 1270^0C for the first ten minutes of firing at half system draft and 1115^oC for the first ten minutes at full system draft. The temperature levels were higher for operation at half system draft than for operation at full system draft. This can be attributed to higher retention of hot gases in the kiln when the draft is low. It is then expected that absence of draft will achieve the highest temperature level in the kiln. But there are problems associated with operation in the absence of draft. The situation leads to excessive pressures in the kiln which is detrimental to the calcinations process. The absence of routing of exhaust gas will lead to possible leakage of hot gases to the kiln casing. This can cause excessive heating and corrosion of the kiln shell. This can also cause flame ‘thrown back’ a phenomenon which leads to instability of flame at the firebox. Excessive draft however can cause extinguishing of burners especially in situation where the burner delivery pressure is relatively low. The temperature levels were lower when operated with limestone feed. This is because of utilization of the heat content of exhaust gases for heating up and heat content of exhaust gases for heating up and calcinations of the limestone. Hence in operation of kilns diligent adjustment of the dampers will be required to achieve the best operating temperatures for calcination. The full draft achieves a negative pressure of 33.8mbar.

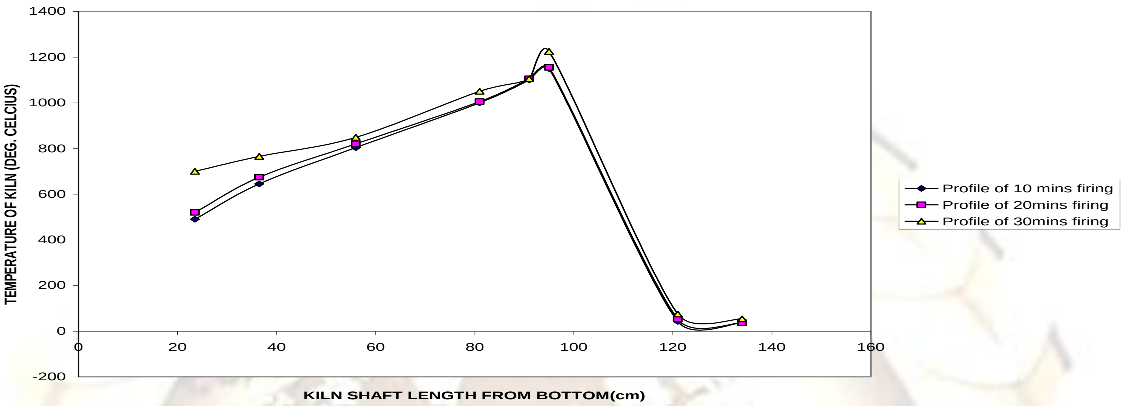

FIGURE 1 KILN TEMPERATURE PROFILE FOR OPERATION WITHOUT FEED UNDER FULL SYSTEM DRAFT

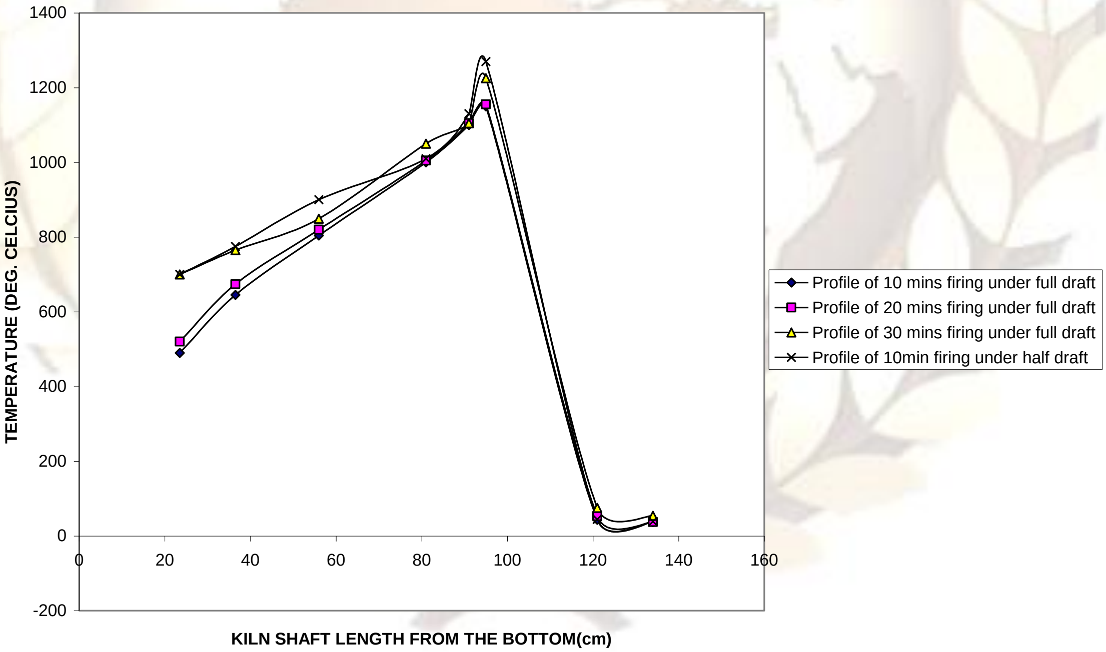

FIGURE 2 TEMPERATURE PROFILE OF THE KILN

From the calcinations model (Hills 1968 [6]) and investigation earlier carried out Okonkwo 3], Okonkwo, Adefila et al [8]), the optimal calcinations temperature of Jakura limestone is 1060^0C the progress of the calcinations of the limestone in the is dependent on temperature, size of limestone and pressure as illustrated in Figure 3 and 4. This also has been established by other researchers[10], Thus the dampers were adjusted to maintain the burning zone at 1060^{0}C.

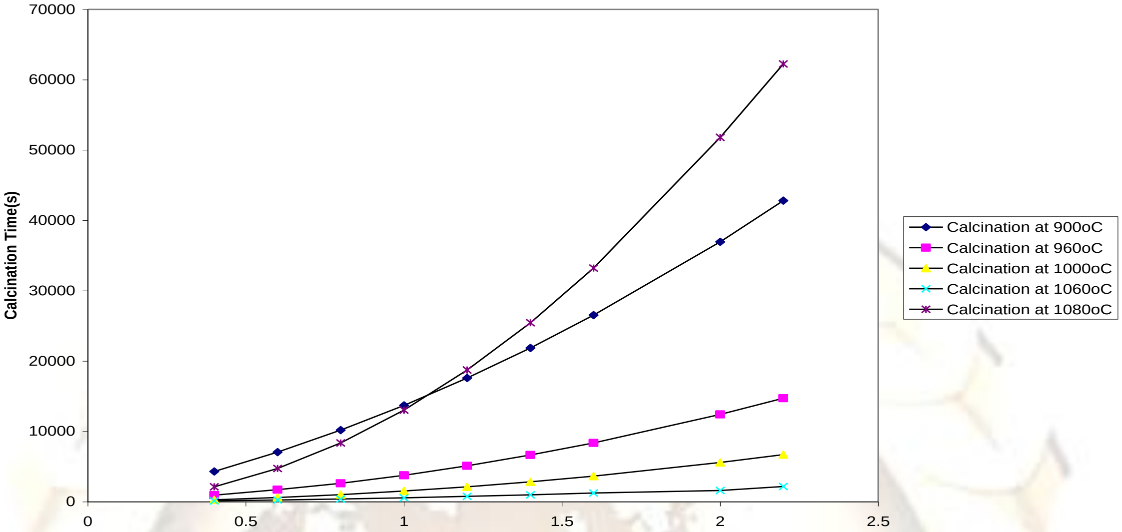

Figure 3 Variation of Calcination Time with Particle radius at -345mmH20(Jakura limestone)

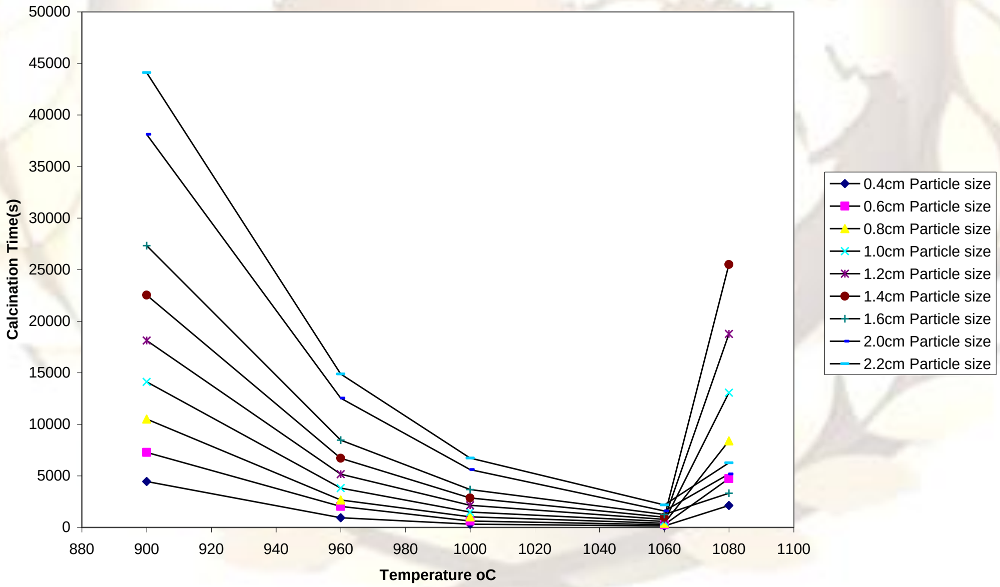

Figure 4 Variation of Calcination Time with Temperature for Jakura Limestone

The limestone charges were calcined for 5, 10, 15, 20 and 25 minutes. The results are summarized in Figure 5 below:

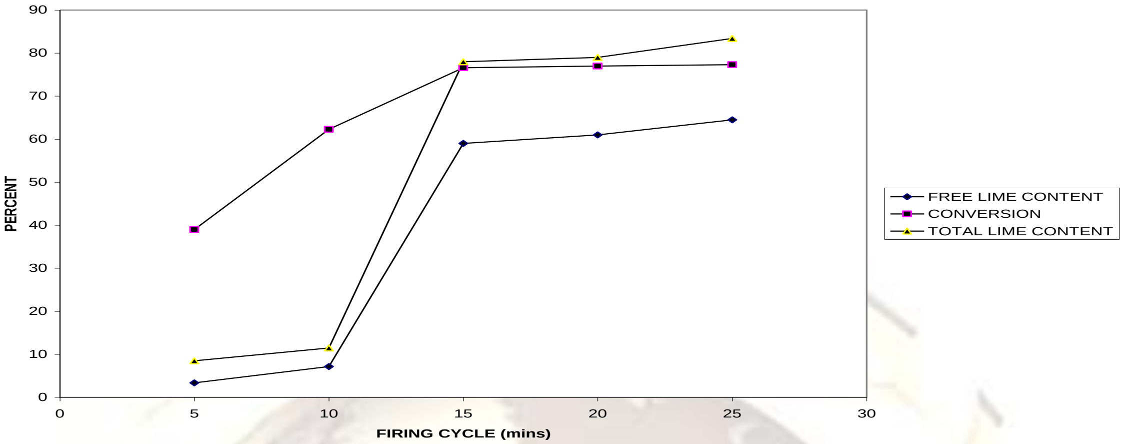

FIGURE 5 CALCINATION RESULTS OBTAINED FROM THE KILN

Predictably calcining for 5 minutes gave the lowest conversion. This is because of the core of the calcining particle. Calcinations for 20 minutes and 25 minutes gave conversion of 79% and 83.4%. The loss in calcinations at this time in spite of being above the theoretically calculated time of 16 minutes can be due to the time required for the particle to achieve the temperature of the burning zone. This therefore implies that there is need to accommodate the required for heating up of the sample to the required temperature. However heating up rate of the limestone was not investigated in the presence work. The closeness of the calculated time and the period of burning which achieved the levels of conversion obtained indicated a good prediction model employed.

5 Conclusion

A vertical shaft lime kiln of 200kg/D was successfully designed constructed and operated based on the process phenomena controlling the calcinations reaction. The low calcinations loss obtained on operation indicates high utility of the kiln mode. The kiln showed a thermal efficiency of 72% and overall kiln efficiency of 61%. The result obtained will stimulate the development of vertical lime kiln technology which will help to solve unemployment problems experienced on large scale in developing economies.

List of Symbols

D = diffusivity of CO_2 in the calcined lime cm^2 sec^{-1}
h = heat transfer coefficient between the outer surface of carbonate sample and the surrounding cal cm^{-2} Sec^{-1}
H = molar heat of decomposition of calcium carbonate cal $gmole^{-1}$
K = Thermal conductivity of calcined lime $calm^{-1}$ sec^{-1} C^{-1}
K_g = mass transfer coefficient to the surface of carbonate sample cm sec^{-1}.
n = rate of decomposition of carbonate sphere $molesce^{-1}$
M_o = mass of carbonate particle before calciantion.
Mt = mass carbonate particle after calcinations
P = total pressure
P_{eq} = equilibrium partial pressure of the calcinations reaction.
P_r = partial pressure of CO_2 at the reaction front
Pp = Partial CO_2 in the calcining particle surrounding
q = heat transfer rate to the decomposing sample J/s
R = universal gas constant J/mol K
R'= universal gas constant in mechanical units cm^3 atm $gmol^{-1}$ K^{-1}
R''= universal gas constant in heat units $calgmole^{-1}$ K^{-1}
r_o = initial radius of particle
r_c = radius of CaCO3 – CaO interface

T = temperature of bulk gas at the surface of the sample
Tr = Temperature at the reaction interface of the calcining particle
Y_{eq} = equilibrium mole fraction of CO_2 at the reaction interface
Yp = Mole fraction of CO_2 in the bulk gas
r = mole fraction of CO_2 at reaction interface.
V = molar volume of calcium carbonate cm^3/g
Γ = diffusive parameter (dimensionless)
Λ = convective parameter (dimensionless)
r* = fractional radius of reaction front r_c/r_o (dimensionless)

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