Computational Fluid Dynamics Modelling of the Rotary Lime Kiln

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ABSTRACT

Rotary kilns are commonly used in industry, from limestone calcination to cement production and waste incineration, among other things. For more than a century, these kilns have been used and developed. In this paper computational fluid dynamics analysis (fluent) is used to simulate and analyse the rotary lime kiln plant. Modelling the combustion characteristics of a large-scale rotary kiln using CFD proved to be a difficult job. The study of rotary lime kiln process, transfer of the heat, and mechanical response of the structure can be applied under the same condition using joint simulation analysis based on FLUENT and ANSYS finite element software, making the simulation results of rotary lime kiln more related to realistic operating conditions. The effect of fuel on the temperature and radiative conditions in the flame is studied. Several fuels like Coal and biomass, as well as other fuels including heavy fuel oil, natural gas, coal gas and corex gas were investigated. After considering many factors like flame temperature, fuel composition, calorific value, environmental consideration we have finalized corex gas as the fuel for our experiment. The calculated approximation of calorific value for Corex gas is around 2000 kcal/N cum. The major components of Corex gas by volume are around carbon monoxide (CO) – 42 %, carbon dioxide (CO_2) – 31 %, hydrogen (H_2) -19 %, Nitrogen (N_2) – 2 %, methane (CH_4) – 1.9 %, moisture – 1 %,and dust content – less than 5 mg/N cum.

Keywords: **Rotary kilns, Modal Analysis, ANSYS Workbench, and Corex gas, CFD, Finite Volume Method**

1. INTRODUCTION

A rotary lime kiln is used to produce quicklime (calcium oxide) through the decomposition reaction of limestone (calcium carbonate).

$$CaCO3+heat \rightarrow CaO+CO2$$

This combustion of calcium carbonate takes place usually at 900 °C (at which temperature the partial pressure of CO2 is 1 atmosphere), but a temperature around 1000 °C (at which temperature the partial pressure of CO2 is 3.8 atmospheres) is usually used to make the reaction proceed quickly. Lime produced with this process is highly calcined (LOI<3%) Lime produced is very useful for steel making process like in ladle furnace, Electric arc furnace and CONARC. Limestone fines and lime fines (0-6 mm) can also be used in sinter plant.

The overall rotary kiln is divided into 3 main zone that is:-(A) Preheating zone/Calcining zone: Preheater towers are kiln structures made up of a series of hot gas ducts and cyclones in which the raw mix is suspended in the kiln exhaust gas and heat is transferred to dry and preheat the raw mix. A pre calciner vessel is found in most preheater towers, where fuel is introduced to aid the calcination process. (B) Burning Zone: The burning zone is at the end of the rotary kiln, where slurry limestone components are heated to about 1350°C -1450°C (2412-2642°F). The temperature in the burning zone must be monitored in order to preserve product quality and kiln productivity. The limestone slurry steadily moves from the cold end to the burning zone before falling out and cooling in the rotary kiln, which is inclined at a slight angle. As a result, temperatures in the kiln vary, making control more difficult. The burning zone has the highest temperatures and accelerates the decarbonization reaction resulting in quick lime (calcium oxide) (CaO). (C) Discharge zone: The clinker cooler receives the lime clinker that has been discharged from the kiln. The clinker is transferred from the cooler inlet to the discharge by perforated grates that reciprocate. Air is blown through the bed of hot clinker in the cooler, bringing it down to near-ambient temperatures. A dam is normally built in the discharge zone of a modern lime kiln. The building of a dam is used to extend the lime's retention time in the kiln. This can be shown in Fig.1.

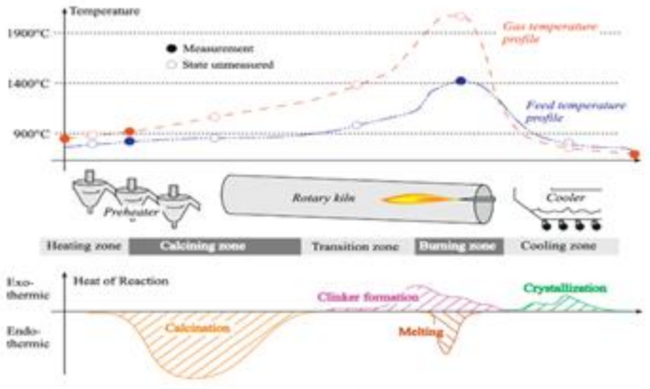

Figure 1: Different zones of Rotary lime kiln

2. LITERATURE REVIEW AND OBJECTIVE

2.1. Literature Review

In their Research Mr. Sarangi Singh Riar et al. [1], investigated thermal energy of three zones i.e. preheater, rotary kiln and cooler, Complex phenomenon associated with the rotary kiln like long time delays, variable feed Characteristics, changing operating conditions, non-linear chemical and thermal reaction makes it very difficult to analyse the complete process. The operational effectiveness of the oven depends on different conditions like like inclination angle, temperature, rotation speed, material flow rate and discharge rate. Mathieu Sellier et al. [2] had researched about Combustion modelling of a rotary lime kiln and concluded that Computational fluid element modelling (CFD) is an effective tool to examine the combustion phenomena happening inside a large-scale rotary lime kiln. After effects of the rotary kiln CFD modelling demonstration shows that the cold air spillages into the systems will have adverse effect as it will increase the secondary air temperature. Du Wenjing et al. [3] had done their study on Experimental Research and Numerical Analysis on Thermal Dynamic Characteristics of Rotary Kiln and concluded that the rotary kiln requires a lot of energy to operate. In this paper, both experimental and mathematical investigations are performed to comprehend the connection between the thermal dynamic characteristics of the kiln and the factors which is related to that. Lately, researchers have built up a few mathematical models to examine the thermal dynamic attributes of the rotating kiln, for example, the 1-D model, 2-D segment model, and 3-D model. Xianghui et al. [4] has done a detailed study of the rings development and its formation inside the kiln which is useful for optimizing the process parameter and reduce the breakdown proportion of the rotating kiln. The rotary kiln has been broadly utilized for the mechanical, physical or synthetic treatment of solid materials in numerous businesses, for example, building materials, metallurgical, chemical and numerous different industries. But if the process is not properly optimized, the raw materials will cling to the internal surface of the kiln during the series of physical and chemical reactions at high temperature. The arrangement of rings in the furnace might be the most concerning issue, which squanders crude materials, wastes powers and raw material and even stops production. Georgallis et al. [5] has seen the formation mechanism of deposits in commercial gas-fired magnetization-reduction roasting rotary kiln was studied. The set down particles in the form of ring clings on the inner surface of kiln wall dependent on the bonding of low melting point eutectic fluid, and the sticky substance clinge on the air pipe head by impact deposition. Studies has indicated that contrasted with different fuels, the use of clean fuel is enormously helpful in diminishing of deposit development rate. Rayko Stanev et al. [6] had researched on the Numerical Modelling and Study of Combustion Behaviour of Rotary Cement Kiln Using Computational Fluid Dynamics and found that Rotary kiln has wide scope of utilization, for example, drying, calcining, iron metal decrease, pyrolysis and titanium dioxide manufacturing and recently rotating furnaces is also used for pyrolysis of wastes. By and large, the principle errand of any rotating kiln as depicted is to give high temperature working condition to drive solid-solid and solid – liquid interaction for clinker development. Rotary Cement furnace is one of the major equipment in concrete industry used to change calcaneus raw substance to clinkers. Now a days Computational liquid elements (CFD) is primary instrument utilized for carrying out the studies in various fields in absence of research facilities and laboratories. This paper shows the flow characteristics which happens inside the Cement rotational kiln utilizing different models of Computational fluid elements. Yongxiang yang et al. [7] had worked on modelling the Combustion Behaviour of Hazardous Waste in a Rotary Kiln Incinerator and observed that Rotary kiln incinerators are generally utilized in the burning of different hazardous substances, for example, fluid, slurry, and solids in large volume, having edge in huge reduction of volume (by 90%) and extensive energy recuperation. Through CFD analysis of the rotational kiln waste incinerator, more understanding was acquired into the waste ignition method. The incinerator is profoundly nonhomogeneous reactor, with high inclination in ignition species and temperature mainly along the rotational oven. Recreation results show that the gas flow is purely in three-dimensional, and the gas blending is very much complicated because of the multi-gas streams and solid heterogeneous responsive nature of the working system, and there is space to improve the blending of the air and the waste streams.

2.2. Objective

Ansys is a huge help to all design engineers. The adoption of Ansys has changed the way we evaluate components before making a final design decision. Ansys helps with design optimization to a considerable extent. It's essentially a solver that helps us simulate loading scenarios on the 3D model of the component. Then we define the boundary conditions and allow the software to mesh the result. This feature plays a vital role in this objective of the study which include:

- To simulate the geometric model using the computational fluid dynamics (CFD) with the implementation of the turbulence model is being engaged with the Standard k-ε model, to obtain the temperature profile and Velocity Profile inside the Rotary lime kiln model.

- To analyse the geometric model component for the velocity profile, temperature profile and molar concentration analysis of the flue gases inside the Rotary lime kiln.

- We can discover what distance maximum temperature occurs and where high flue gas velocity is produced by evaluating the results (post processing), all of which can offer us a virtual grasp of what happens to the Rotary lime kiln when it is employed in the real world.. We can then improve the design if any of the temperature, velocity, molar concentration etc. is more or less than the desirable value, also we have to optimize the results using different boundary conditions.

3. Methodology

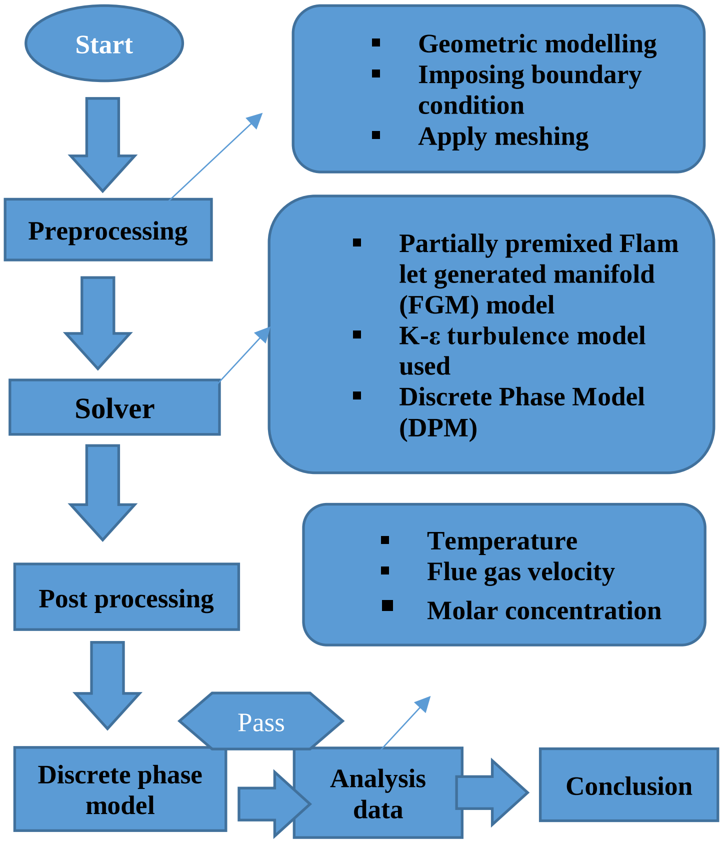

Figure 2: Methodology

Basically any Simulation problem is divided into 3 parts as shown in Fig.2 i.e. 1) Pre-processing 2) Solver 3) Post processing/ Solution. Pre-processing basically deals with the preparation of the model, discretizing the model and applying boundary condition to the model. Solid modelling and direct generation are the two methods for producing a finite element model. I am basically using solid modelling for my project. The solid modelling method employs Primitives (pre-defined geometric shapes) and procedures similar to those found in computer-aided design (CAD) software. The geometric model, also known as the three-dimensional (3D) CAD model, is a crucial representation for physical system design. A standard CAD tool can compute component mass properties and can be used in conjunction with other engineering analysis tools to assess other physical properties such as stress and thermal profiles. The main purpose of this φ3.0×30m rotating kiln is to calcinate limestone. The rotary kiln's cylinder body is 3.5 percent (sinusoidal) inclined from the horizontal plane. This can be seen in Fig.3 and Fig.4.

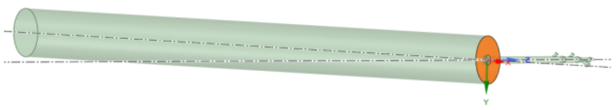

Figure 3: Isometric View of rotary lime kiln

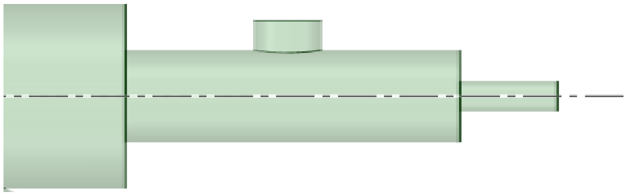

Figure 4: Front View of rotary lime kiln burner

Details of Boundary Conditions CFD Models for Combustion are as follows

- Dimension of the Rotary lime kiln
  Diameter = 3 m, Length = 30 m
  Thickness = 0.01 m, Angle of inclination = 3.5°c
  Speed (rpm) = 3, Ambient condition=27 °c
  Inlet Temperature of kiln =800 °c
  Outlet Temperature of kiln: 1050 °c

1. Burner design input data
   Type of fuel: Coal gas, Air to fuel ratio: 3.24
   Type of burner: Low NOX, Air staged burner.
2. Inlet of Fuel and Mixture
   Mass flow rate of Particles =140kg/min
   Total Mass flow rate of fuel =100.3 m3/min
   Pressure of the fuel at inlet = 18 KPA
3. Inlet of Air
   Total Mass flow rate of Primary Air =45.4 m3/min
   Pressure at the entry of Primary air =29.4 KPA
   Total Mass flow rate Secondary air Air =280 m3/min
   Pressure at the entry of Secondary air =6.8 KPA

As we know that simulation is a very complex process, and it involves too much of time and costs so we have to proceed with some assumptions which make the simulation process smooth: - 1. Flow is assumed to be steady and turbulent. 2. Particles are of uniform size. 3. Uniform inlet temperature of the particles. 4. Assuming uniform heat transfer to the ambient. 5. Standard value for convective heat transfer coefficient, emissivity and ambient temperature is considered. 6. Flame is equally distributed in all the direction. 7. Any effects of the rotating wall have been ignored in this work.

Mesh model of burner and Rotary lime kiln is shown in Figs. 5 and 6. Meshing is a highly important stage or plays a big role in the simulation process once the geometric modelling phase is completed and successfully loaded into the Ansys module for further simulation. Meshing is a step in the engineering simulation process that involves breaking down complex geometry into simple elements that can be utilized as a discrete local approximation of a wider domain. Because the shape of the burner is intricate, I utilized a polyhedral element to mesh it. Polyhedral elements for complicated geometry provide good mesh quality, less skewness, faster convergence, and a smaller number of cells, all of which contribute to lower computing costs. Rotary kiln is simple in shape so hexahedral mesh element is used for that, because modifying a Hexahedral mesh is much easier by moving a line of nodes.

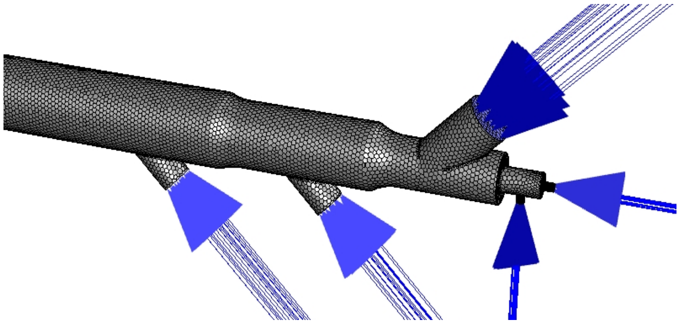

Figure 5: Mesh Model of Burner

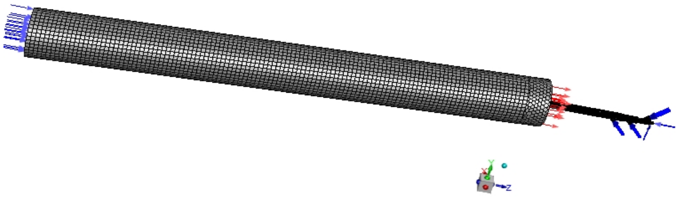

Figure 6: Mesh Model of Rotary lime kiln

CFD solutions use the finite volume approach to solve mass, momentum, species, and energy equations numerically. The Finite Volume Approach (FVM) is a discretization approach for approximating the conservation, or balancing, of one or more values given by a single partial differential equation or a set of partial differential equations. A mesh is generated, similar to the finite element method, by dividing the domain in which the space variable exists. Control volumes are the mesh's components. Integrating the PDE across each control volume yields a balancing equation. The set of equilibrium equations is then discretized in terms of a set of discrete unknowns. . The key challenge is the discretization of the fluxes at the control volume boundaries: the numerical fluxes must be discretized in order for the FVM to be efficient.

1. Conservative, i.e. the flux entering a control volume from its neighbour must be the polar opposite of the flux entering the control volume from its neighbour.
2. Consistent, i.e. a regular function's numerical flux as the mesh size decreases, interpolation tends to become a continuous flux

3.1. Governing Equation

1. Mass Conservation Equation:

$$\frac{\partial U}{\partial x}+\frac{\partial V}{\partial y}+\frac{\partial W}{\partial z}=0$$

2. Momentum Conservation Equation: Each term = Force/Volume

$$\rho\nabla.\left(U\vec{V}\right)=-\frac{\partial P}{\partial x}+\nabla.\left((\mu+\mu_t)\nabla U\right)$$

$$\rho\nabla.\left(V\vec{V}\right)=-\frac{\partial P}{\partial y}+\nabla.\left((\mu+\mu_t)\nabla V\right)$$

$$\rho\nabla.\left(W\vec{V}\right)=-\frac{\partial P}{\partial z}+\nabla.\left((\mu+\mu_t)\nabla W\right)$$

3.2. Numerical modelling of combustion

- Partially premixed flame let generated manifold (FGM) model

Practical system involves combustion of non-premix and premix combustion that is called partially premix combustion or stratified combustion. The non-premixed flame let model considers the 1D diffusion flame to be the underlying chemical structure that makes up turbulent flames, with the chemical source term mostly balanced by diffusion processes.

- **K-epsilon turbulence model**

The K-epsilon model is one of the most extensively used turbulence models, yet it fails catastrophically when massive adverse pressure gradients are present. It's a two-equation model, which means it has two more transport equations to account for the turbulent characteristics of the flow. This allows a two-equation model to account for historical effects such as convection and turbulence diffusion energy using only two equations.

Rans equation

$$\frac{\partial}{\partial x}(\rho c^{-}) +\boldsymbol{\nabla}\,(\rho v^{-} c^{-}) = \boldsymbol{\nabla}\,(\frac{\mu}{Sc}\,\boldsymbol{\nabla} c^{-}) + \rho S^{-}$$

- **Discrete Phase Model (DPM)**

In addition to solving transport equations for the continuous phase, Fluent allows you to simulate a discrete second phase in a Lagrangian frame of reference. Spherical particles make up the second phase (which may or may not be spherical). In a continuous period, scattered. The heat and mass transfer to and from these discrete phase entities, as well as their trajectories, are computed using FLUENT. It is possible to include phase coupling and its effects on both discrete phase trajectories and continuous phase flow. The particle tracking is relatively unsteady over time.

4. RESULTS AND DISCUSSION

We can comprehend the Rotary kiln behaviour using computational fluid dynamics in the various scenarios described above. For examples, the velocity contours, streamlines of Flue gases, molar concentration of species, and temperature contours are discussed. The temperature profile of rotary lime kiln and burner is shown in figure 7. High temperature is found near the combustion reaction zone, and normally limestone breaks to lime in the temperature range of 1200 °c to 1500 °c, So the temperature in the rotary kiln is maintained in this range to initiate and complete s the reaction. The velocity contours are depicted in Figs 8 and 9. High velocity of the flue gas is found in the burner zone where air and coal gas are feed from the primary and secondary air and fuel inlet zone which is then directed to the lime kiln zone where the heating value of this fuel is used to initiate the decomposition reaction of the limestone. The flow inside the lime kiln is represented in Fig. 10.

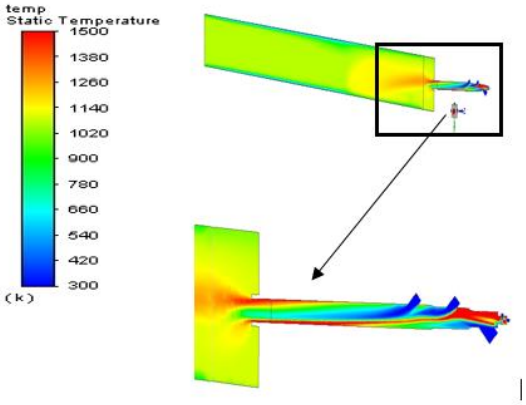

Figure 7: Temperature profile of Rotary lime kiln and kiln burner

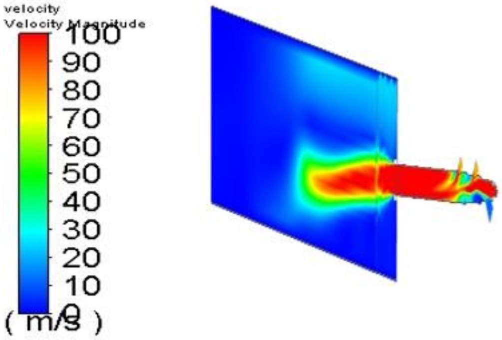

Figure 8: Velocity Contour of Flue Gas

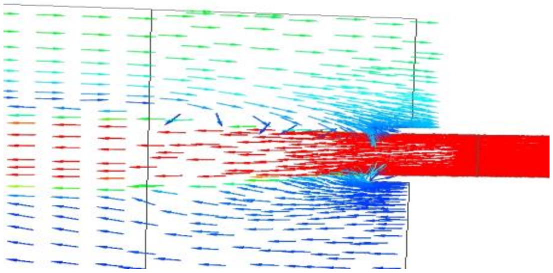

Figure 9: Velocity Vector of Flue Gas

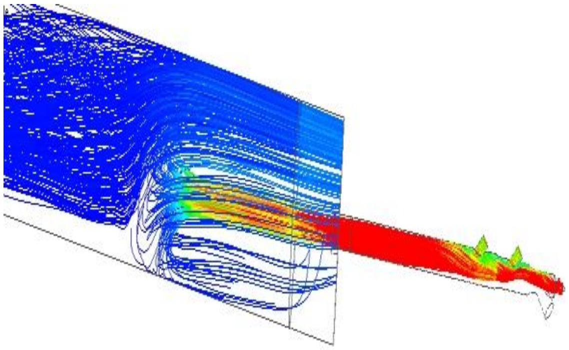

Figure 10: Plot of streamline of flue gases

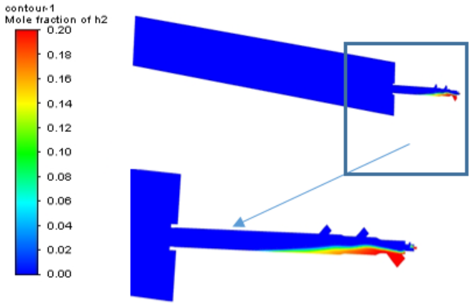

Figure 11: Molar Concentration of Species-H_2

The flow inside the lime kiln is turbulent which can be shown with the help of the streamline of the gas. The molar concentration of species H_2 is shown in Fig.11. Hydrogen gas concentration is found mainly at the burner zone where a definite quantity of hydrogen is required for the combustion of the coal gas and air.

5. CONCLUSIONS

CFD results have been presented for velocity, temperature and molar concentration of fuel and oxygen along the rotary kiln axis. Higher concentration of hydrogen is lower part of burner and lower in in the upper part of burner due to higher flow rate of air. High temperature is observed near burner outlet in the Rotary lime kiln. As a distance from burner outlet increases the flue gas temperature decreases mixing of fuel and air can be improved in the burner by fixing their inlet opposite side of burner.

6. ACKNOWLEDGEMENTS

This experiment is mainly performed in Arcelor Mittal Nippon Steel company.

NOMENCLATURE

U,V,W	Velocity in X,Y,Z Direction	[m/S]
X,Y,Z	Co-Ordinate System	[m]
ρ	Density of Fluid	[kg/m^3]
p	Pressure	[N/ m^2]

REFERENCES

[1] Mr. Saranjit Singh Riar, Mr.Vaibhav H. Bankar, Mr. Pratik P. Chaphale, A Review on Design and Thermal Analysis of Rotary Kiln for Lime Production, International Journal on Recent and Innovation Trends in Computing and Communication Volume: 4 Issue: 5

[2] Mathieu Sellier, Mark Jermy, Combustion modelling of a rotary limekiln, Progress in Computational Fluid Dynamics An International Journal ,2010

[3] Du Wenjing, Wang Bing, Cheng Lin, Experimental Research and Numerical Analysis on Thermal Dynamic Characteristics of Rotary Kiln, The Canadian Journal of Chemical Engineering, April 12 2018.

[4] Xianghui Fu, Zezong Chen, Xiangyang Xu, Lihue He 1 and Yunfeng Song 1, Deposits in Gas-Fired Rotary Kiln for Limonite Magnetization-Reduction Roasting: Characteristics and Formation Mechanism, School of Metallurgy and Environment, Central South University, Changsha 410083, China, 2019.

[5] M.Georgallis, Nowak, M.Salcudean and I. S. Gartshore, Three-dimensional modelling of rotary lime kilns , Department of Mechanical Engineering, university of British, Canada (2002)F. M. White, Fluid Mechanics, McGraw-Hills, New York, USA, 2011.

[6] Rayko Stanev , Iliyan Mitov , Eckehard Specht , Fabian Herz, Geometrical characteristics of the solid bed in a rotary kiln, Department of Physical Metallurgy University of Chemical Technology and Metallurgy Bulgaria (2013)

[7] Yongxiang yang, marc j. A. Pijnenborg, markus a. Reuter & joep verwoerd, modeling the combustion behavior of hazardous waste in a rotary kiln incinerator, department of applied earth sciences, delft university of technology, Netherlands (2014)