PERFORMANCE STUDY OF ROTARY KILN HAZARDOUS WASTE INCINERATOR

A thesis submitted in partial fulfillment of the requirements for the Degree of
Master of Technology
In
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UNIVERSITY OF PETROLEUM & ENERGY STUDIES
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CERTIFICATE

This is to certify that the work contained in this thesis titled **"PERFORMANCE STUDY OF ROTARY KILN HAZARDOUS WASTE INCINERATOR"** has been carried out by **Mr. Arun Kumar Dubey** under my supervision and has not been submitted elsewhere for a degree.

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NOMENCLATURE

$\dot{q}_h$	Heat Rate Required
Q	Gas Volume Flow Rate
ρ_g	Gas Density
H	Enthalpy
C_p	Specific Heat
T_0	Reference Temperature
C_A	Concentration of pollutant A
k	Kinetic Rate Constant
n	Reaction order
E_{act}	Activation Energy
$Q_{exhaust}$	Exhaust flow rate
v_T	Gas velocity in the incinerator
t_r	Residence time
Q_f	Heat generated by combusting the fuel .
Q_g	Heat going to the load.
Q_l	Heat lost through wall.
Q_p	Heat Carried out by exhaust products.

ABBREVIATIONS

ICHWMF	Integrated Common Hazardous Waste Management Facilities
GEPIL	Gujrat Environment Protection Infrastructure Limited
GPCB	Gujrat Pollution Control Boar
CPCB	Central Pollution Control Board
SCC	Secondary Combustion Chamber
PCC	Primary Combustion Chamber
GCV	Gross Calorific Value
LOI	Loss of Ignition
HRS	Hours
RKI	Rotary Kiln Incinerator
LHV	Lower Heating Value
HHV	Higher Heating Value

SYNOPSIS

PERFORMANCE STUDY OF ROTARY KILN HAZARDOUS WASTE INCINERATOR

Objective-

Performance study of rotary kiln hazardous waste incinerator.

Description-

The mathematical behaviors of such a system include a variety of interactions that depend on the phase flow and reaction. After the feed is injected into the rotary kiln, feed immediately evaporates due to intimate contact with the fuel oil at a high temperature. This study include all components such as

- Heat Transfer Effect
- Combustion Kinetics and Stoichiometric Calculations
- Working plant condition data sheet for the performance evaluation of rotary kiln.

So, for better operation, control and pre-estimation of inlet and outlet conditions, a mathematical equations of an incinerator is to be made. This will be done by using material balance, component balance, heat balance and thermodynamics involved for the various types of waste. These equations also help to find out the heat recovery and plant operability of the plant in terms of safety as well recovery.

Expectation-

This study will predict important aspects of its overall performance and several trends involving parametric variations in its operation. This work, when further validated using literature and other experimental data, will provide an exciting tool for tuning the operation of existing kilns, and to provide a systematic basis for the efficient design of new kilns.

The Hazardous wastes (Management & Handling) Rules' 1989 and as amended 2000,2003 and 2008; under Environment (Protection Act), 1986 ban indiscriminate disposal of hazardous wastes and directs the hazardous wastes generating unit; here after referred as "The Generator" to treat and dispose off their hazardous wastes in environmentally safe manner. The industrial wastes mentioned in schedule-I and schedule-II of the rules have been categorized as hazardous wastes.

At the same time they permit the industries to dispose off their wastes in safe & secured manner. It has been made mandatory by the government to dispose off Hazardous waste in systematic and scientific disposal way and pollution control boards have been asked to ensure it. For systematic & scientific disposal of hazardous wastes, a facility can be constructed where care is taken to avoid any negative effects on the environment. These facilities are called as Secured Landfill Facilities. The opportunity in Surat region is very high as it is industrially growing belt. ICHWMF (Integrated Common Hazardous Waste Management Facility) is a community-based approach for the management of hazardous wastes generated by the cluster of Industries in the region. The facility is supposed to make all the hazardous waste generating industries their members, collect the hazardous wastes from them, transport the same to the facility, treat and dispose these wastes at the facility, as per the legal requirement and in the environmentally suitable manner

Vision and value:

At GEPIL, Values are what we have held sacrosanct, all through our existence as an organisation. Over the last two decades, it has been our constant attempt to build the Group on a strong foudation of Values. One of our challenges has been to continuously adapt our values to the environment and make it relevant while remaining strong at the core. Our strong foundation in values, our deep expertise in different businesses, and our presence and goodwill in the marketplace gives us the opportunity to propel ourselves into an intense and exciting future.

"Innovations for a Better Life" - is the vision which has been inculcated for breathing in our manifesto.

"Environment comes first" - is the values consistenly taught to all who work for the group. As a "life environment creation company," we assume the social responsibility indispensable to society and endeavor to secure quality in every aspect, including safety, durability, and environmental consciousness.

Mission:

"To be a Strong and Quality conscious by laying the foundation of the future in the areas of Infrastructure Development and Environment Management."

The Gujarat Enviro Protection & Infrastructure Limited would fulfill the infrastructural & environmental needs through various end of the pipe treatment projects, "Industrial solid / Hazardous waste management facility", Research to Recycle waste or Reuse waste and by implementing the best technologies available worldwide. The mission is to plan & implement Infrastructural Environmental projects on **"BUILT OWN & OPERATIONAL BASIS".**

Status:

- The company has received the necessary authorization from GPCB and has become operational.

- Gujarat Enviro Protection and Infrastructure Ltd. is a company registered under the companies act, Registration No. 04-35306 of 1998-99 on dt. 21/10/1999, with a target to meet the environmental & infrastructural needs of this region.
- It is promoted by Luthra Group of Companies. The company has a written environmental policy, a certified IS0 14000 Company.
- The Luthra Group of Companies, which made a modest beginning in the textile trading, in 1960, and has presently, established its goodwill in the areas of textile processing, textile exports, waste minimization, Eco-friendly, and pollution prevention technologies.
- The mission of the Company is to provide Integrated Common Hazardous Waste Management Facility (ICHWMF) for the industries throughout India.

Integrated common hazardous wastes treatment, storage and disposal facility for the state of Gujarat

The treatment and disposal of hazardous waste is a highly technical, requiring multi-skill, very expensive and not so established subject in the country. The development of individual hazardous waste treatment and disposal facility is neither technically feasible nor economically viable and more importantly environmentally detrimental and highly risk oriented proposition. In order to therefore manage the hazardous wastes safely, with the best possible technology at an affordable cost, the community concept of Integrated Common Hazardous Wastes Treatment, Storage and Disposal Facility (ICHWTSDF) comes into the existence.

In this concept, the facility is supposed to make all hazardous wastes generating industries their members, collect the hazardous wastes from them, transport the same to the facility, treat and dispose these wastes as per legal requirement and in environmentally suitable manner. As per the Polluter Pays principle, the generator pays for the services provided by the facility.

Rotary kiln incinerators are widely used in the incineration of various hazardous wastes such as liquid, sludge or solids in bulk or in packages. The benefits lie in the drastic volume reduction and substantial energy recovery. The main objectives of the incineration are the complete combustion of the waste materials and the efficient recovery of the thermal energy from the off-gases after the waste combustion. Emission control of certain remaining species in the off- gases such as CO and dioxins is an important criterion for the operation. The complete destruction of hazardous compound depends very much on gas mixing extent of air and various streams, the distribution of gas temperature and resistance time within the kiln and secondary combustion chamber (SCC). Due to large variations waste types and difficulties in feed characterization of physical, chemical and thermal properties the complex transport and chemical process within the kiln are not well understood, and thus the incineration process often anticipates substantial but unpredictable fluctuation of gas temperature within the system. The temperature fluctuations lead to uncertainties in the process chemistry and difficult in emission control. The high calorific waste can be used in energy intensive industries to replace primary fuels, and thus only the most difficult types of waste are delivered for incineration in rotary kilns. All the waste averaged and modeled as a global fuel. Then the subsequent combustion modeling has been conducted by defining each individual waste stream by using the artificial fuel mixture. A number of the waste- to -energy facility operating in the world utilizes a rotary kiln combustor as the principal treatment unit in their systems. Waste if fed to the kiln from the receiving system and the products of combustion are treated and released. The combustion gases are polished in the secondary combustor, cleaned of acidic components and particulates, and sent to stack. Bottom ash is cooled, mixed with fly ash, stabilized and land filled.

Because of concerns for full burnout of the combustible in the feed, the destruction of toxic organic, the segregation and collection of toxic meals, and efficient collection of energy, developers and operator of kiln combustors must have a thorough understanding of the operation of each element of their waste-to-energy facility and of the integration of these elements.

Rotary kilns are found many processes that involve solid processing. These include drying, incineration, mixing, heating, cooling, humidification, calcinations, reducing, sintering and gas- solid reaction. The most common and industrial important of rotary kilns is in the cement production: all major producer use the rotary kiln as their equipment of choice. Cement kilns can be very large.

Another important of the rotary kilns is for the incineration of waste materials. Rotary kiln are popular for this role because of their flexibility. They can handle large variety of feed materials, with variable calorific value, and removal of waste solids at exit present no problems. Typically hazardous waste incinerators operates with relatively deep beds, and have a secondary combustion chamber after the rotary kiln to improve the heterogeneous combustion of waste. An example of such a hazardous waste incinerator is shown below.

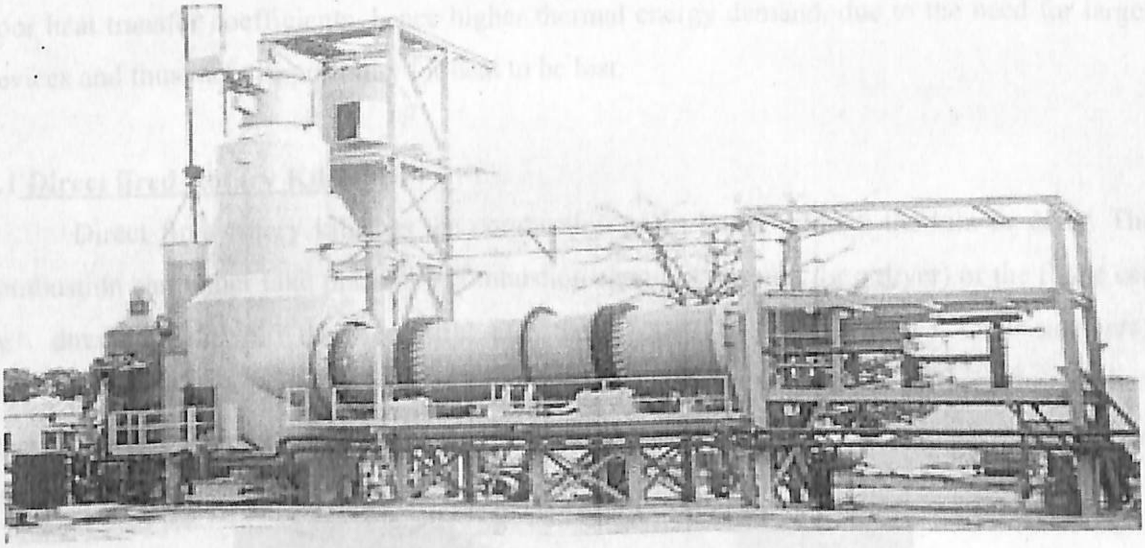


Figure 1.1 - A rotary kiln waste incinerator with a vertical secondary combustion chamber.

In the mineral processing industry, they are many applications in rotary kiln:- some of the applications that have been published that are magnetite oxidation, induration of iron ore pellets, coke calcining, and drying.

Rotary kilns are amongst the most well-established unit operation in the process industry. They can be used for three purposes: heating, reacting and drying of solid material, and in many cases they are used to achieve a combination of these aims. In the design of kilns, there are four important aspects to consider from a process engineering point of view, and these are heat transfer, flow of material through rotary kiln, gas solid mass transfer and reaction.

Rotary kilns are one of the most widely used pieces of processing equipment. They are used for drying or calcining a variety of products including sand, aggregates, limestone and food products. With an ever increasing focus on reducing greenhouse gas emissions, the continued or increased use of rotating kilns can only be achieved by reducing the thermal and electrical energy consumption used in these processes. Heat transfer in kilns is very complex, with radiation, convection and conduction all contributing to energy transfer between the gas, the feed and the vessel wall. A fluid bed calciner or dryer achieves rapid drying by the large heat transfer coefficient obtained through the high air volume being circulated. The penalty is the increase in electrical energy required to circulate this high air volume. Rotary kilns on the other hand have poor heat transfer coefficients, hence higher thermal energy demand, due to the need for larger devices and thus more opportunity for heat to be lost.

1.1 Direct fired Rotary Kiln

Direct fired rotary kiln has the combustion gases going through the kiln or dryer. The combustion can either take place in a combustion chamber (normal for a dryer) or the flame can be directed down the length of the rotary kiln (typical for calciners). In a drying application, the contact between the gases and the solids is the primary form of heat transfer. In a calcining application, the radiation from the flame is the primary form of heat transfer.

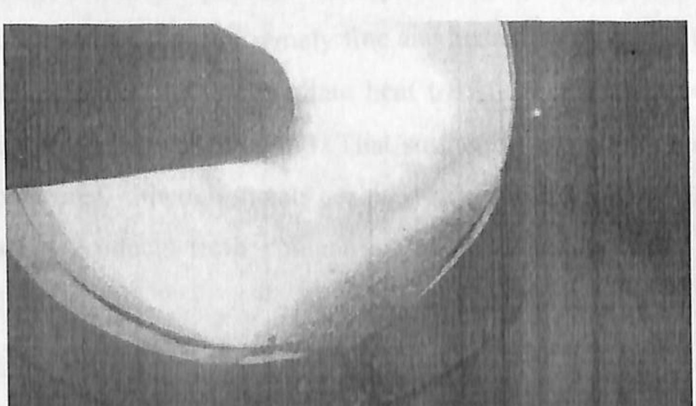


Figure1.2 Direct Fired Rotary Kiln

Rotary kilns can operate in either the co-current mode where the gases and solids move in the same direction or in the counter-current mode where they move in opposite directions. The kiln can also be operated in either the reduction or oxidation mode.

Radiation is the primary mode of heat transfer. Direct fired rotary kilns from Thermal Processing Solutions can be supplied gas or oil fired in a parallel flow or counter flow arrangement. In a direct fired kiln, heat transfer rate and process atmosphere composition/volume are dependent, therefore consideration must be given to the compatibility of the process material with the process gas composition as well as the gas velocity. In addition to the combustion products, other gases such as steam can be introduced into the kiln atmosphere.

1.2 Indirect Fired Rotary Kiln

Indirect fired rotary kiln the combustion or other form of heating takes place on the outside of the rotary kiln shell. This way, the material being processed does not come into contact with the combustion gases. This can be important to the product quality or to keeping the product from reacting to the gases. Another advantage is that the amount of gases coming from the kiln that need to go through an emission control system is very small. An indirect fired rotary kiln can be supplied either gas, oil or electrically heated, and usually feature multiple furnace zones. In an indirectly heated, the process material is isolated from the heat source consequently heat transfer and the process atmosphere composition/volume are independent. Therefore the process material can be extremely fine and heated in a very controlled manner with a desired atmosphere. In this some intermediate heat transfer surface between the combustion products and the load, as shown in Figure 1.3. That surface is commonly some type of ceramic due to the high temperatures, although metals are used in some cases. The surface is designed to prevent the combustion products from contacting the load and reducing the quality of the finished product.

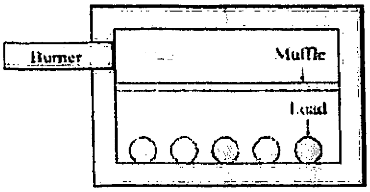


Figure 1.3 Elevation view of an indirect-fired furnace.

The first published experimental studies on rotary kilns recorded the relationship of rotation speed and kiln inclination on bed depth and solids residence time (Sullivan et al, 1927). A model was later developed based on the assumption that particles in a rolling bed move in a circular motion with the rotation of the kiln, and then fall down the surface of the bed in a thin layer (Saeman et al, 1951). The time taken to fall down the surface was assumed to be small compared to the time for a particle to move with the kiln from the bottom half to the top half of the bed. Using the geometry of an inclined rotary kiln, the angle of inclination necessary to maintain a constant bed height over the length of the rotary kiln could be determined for a given rotation speed. This basic model predicted the original data (Sulllivan et al, 1927) well, and the model was further refined to predict axial movement of particles with different bed fills, taking into account the time for particles to fall down the surface of the bed (Kramers and Crookewit 1952). In later work that specifically measured the movement of particles at the surface of the kiln, the validity of the model of Kramers and Crookewit (1952), with minor exceptions, was confirmed (Lebas et al, 1995). More recently, the same fundamental model of the path of particles was shown to be correct in a study of particle motion where there is no net axial flow of particles in a rotating drum (Spurling et al, 2000).

Jauhari et al. (1998) measured mass transfer in a rotating drum by measuring the evaporation rate of decane from impregnated alumina particles. Most of the measurements were done using shallow beds with baffles (flights) fitted to the rotary kiln.

Yongxiang YANG, Marc J.A. Pijnenborg and markus A. Reuter has done modeling of the fuel stream and combustion in a rotary- kiln hazardous waste incinerator. For better understanding of the incineration process, process simulation was conducted using computational fluid-dynamics code Phoenics to characterize temperature and species distribution in the incinerator. In this paper hazardous waste in various from is firstly converted to a hydrocarbon-based virtual fuel mixture. The combustion of the simplified waste was then simulated with a 7-gas combustion model.

2.1 Overview of developed area in rotary kiln

These Literature survey includes various area of chemical Engineering such as mass transfer, diffusion effect, Heat transfer or thermal equation, combustion system inside the rotary kiln.

2.1.1 Mass transfer in rotary kiln
2.1.2 Diffusion effect in rotary kiln
2.1.3 Heat Transfer effect in Rotary kiln
2.1.4 Hydrodynamic and dispersion in active layer of rotary kilns.
2.1.5 Kiln combustor system of rotary kiln

2.1.1 Mass transfer in rolling rotary kiln

This model is given by M.D. Heydenrych *et al.* He took mass transfer effect in rotary kiln. He divided the rotary kiln in different layer as shown below.

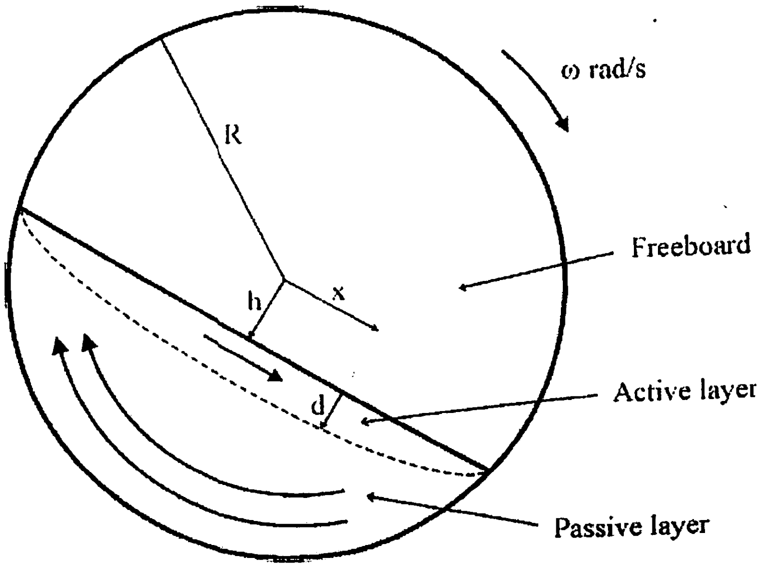


Figure2.1. Radial cross section of a kiln, showing the nomenclature

The movement of gas in the interparticle voids in the bed of the kiln is considered, where particle moves concentrically with the geometry of the kiln and gas is entrained by these particles. A reactor approach has been used to derive effectiveness factor for the bed as a function of bed fill, reaction kinetics and rotation speed. In many cases, the entrained gas becomes depleted within the bed, leading to the simplified model for the bed effectiveness factor. At faster rates, mass transfer can be much higher than the model predicts, indicating that other mechanisms, such as dispersion or diffusion are also important in these conditions.

He considers the mass transfer to occur by the inclusion of gas in the interparticle voids in between the particles that move concentrically with the kiln. By doing so, the rate of mass transfer was found to be dependent on bed fill and the ratio of reaction rate constant to angular velocity (k/w). The model was found to be valid at slow to medium fast reactions.

Here it is examined that the mass transfer in the rotary kilns and has been proposed an approach to describe the phenomena that describe the rate of mass transfer.

2.1.2 Diffusion Effects in Rotary Kiln

The previous worker has done the same model of diffusion effect also. Mass transfer model considers the mass transfer to occur by the inclusion of gas in the interparticle voids in between the particles that move concentrically with the kiln. By doing so, the rate of mass transfer was found to be dependent on bed fill and the ratio of reaction rate constant to angular velocity (k/ω). The model was found to be valid at slow to medium fast reactions. For fast reactions it under predict mass transfer. Therefore the model will be extended to diffusion effects. An additional dimensionless number is necessary then to describe the system. This can either be a Peclet number $\left(\omega R^2 / D_e\right)$ or a Thiele modulus $\left(kR^2 / D_e\right)^{1/2}$. The solution of the 2-dimensional partial differential equations that describe the extended model gives a handle on the effect of scale-up in rotary kilns.

This approach takes into account the inclusion of gas in the interparticle voids in between the concentrically moving particles in the passive layer of the bed. In that work, the role of the active layer where particles move along the surface of the bed was ignored by assuming that the thickness of the active layer region is infinitely thin. They concluded that their concentric movement model has merit, but that the effect of diffusion and dispersion within the bed must also be taken into account in the case of fast reactions. Now it is explored the effect of diffusion within the concentric flow region, and how it affects the overall mass transfer, again under the assumption of an infinitely thin active layer.

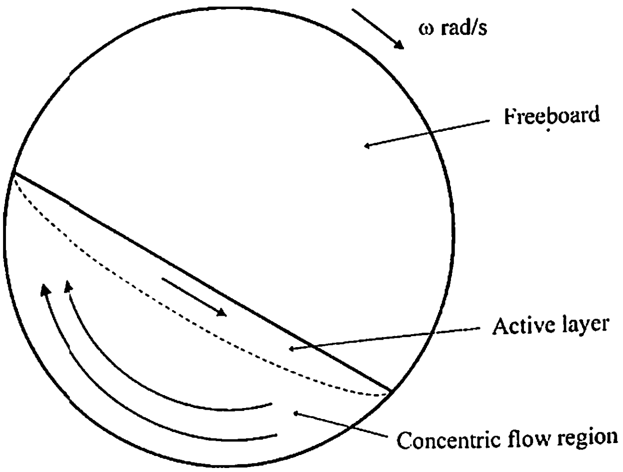


Figure2.2. shows the concentric movement and active layer regions

2.1.3 <u>Heat Transfer Effect in Rotary Kiln</u>

Various equations of heat transfer have been developed for rotary kiln. The combined radiation and convection Heat transfer is the total heat input in the bed. By assuming that the bed is also well mixed and axially moves in plug flow, the axial gradients of bed temperature and gas temperature could be related to the local rates of gas-to-exposed bed and wall-to-covered bed heat transfer by ordinary differential equations (Sass,1967).

This allows one to establish a representative average bed temperature at each axial location. One of the first early representations of one-dimensional modeling was done by (Sass, 1967)

$$\frac{dT_s}{dz} = \frac{1}{C_{ps}G_s}\left[\alpha_2\left(T_g - T_s\right) + \alpha_3\left(T_w - T_s\right)\right]$$

Where $\alpha_i = h_i A_i$ is the product of heat transfer coefficient h of the interface with area A, C_{pg} and C_{ps} are the specific heat of gas and solids respectively, T is the local thermodynamic temperature, and G is the mass flow rate.

These equations formed the basis for the various one-dimensional kiln system that have appeared in the literature (Brimacombe and Watkinson,1978; Wes et al., 1976; and others). In these models an energy balance on the wall must be included, as well as the kinetic expression for any reactions. The latter led to set of mass conservations that must be solved along with the energy equation. For Example, if evaporation of free moisture is controlled by heat transfer, rather than mass transfer, an additional thermal balance on the moisture can be included as

$$\frac{dW}{dz} = \frac{1}{G_1 \lambda}\left[\alpha_1 (T_g - T_s) + \alpha_3 (T_w - T_s)\right]$$

$$\lambda = \lambda_0 + C_V (T_g - T_s)$$

Where W is the mass of water, λ_0 is the latent heat of liquid water, and Cv is the specific heat of water vapor.

2.1.4 Kiln combustor system

James T. Cobb, Jr. and K. Banerjee has given the mathematical analysis of a municipal solid waste rotary incinerator.

In this study the kiln is divided into two active zones - a first zone for pyrolysis and a second zone for combustion. The model for the pyrolysis zone relies upon the following assumptions:

- Bed height decreases linearly with distance along the kiln's centerline;
- The bed is well mixed in the vertical direction;
- Only convective heat transfer from the gas to the bed is considered; the kiln wall is assumed to be refractory-lined, thus no heat is transferred through the barrel;
- The temperature in the product gas above the bed is constant throughout this zone of the kiln; its value is calculated by the method of Tillman [l];
- Both the solid and gas regions operate in the plug-flow regime.

The model for the combustion zone is based upon the model for zirconium combustion, developed by Lemieux et al. The bed depth and the uniform temperature throughout the bed are set at the values obtained at the exit of the pyrolysis zone. The model determines the burning rate of the char and calculates the char mass flow profile across the combustion zone. The bed is axially divided into slices of uniform surface oxygen concentration and each axial slice is divided vertically into segments of uniform oxygen concentration and particle size. A mass balance is performed on the slices in the vertical direction, yielding an ordinary differential equation describing diffusion of oxygen through a porous solid, with boundary conditions at the wall-solid and gas-solid interface. The particle burning rate is combined with equations used to describe oxygen transport through the bed. Oxygen is assumed to be at a uniform concentration at each bed depth location, and the particles are assumed to be small enough that oxygen is at a uniform concentration in the gas surrounding each particle. The resulting finite difference equations are solved using a tridiagonal matrix algorithm.

The residence time of char in the kiln was calculated as.

$$\theta = \frac{0.19\,L}{NDS}$$

Where,

θ------→ is expressed in minutes,

L-------→ is the kiln length,

D------→ is the kiln diameter,

N------→is the number of revolutions of the kiln per minute and

S-------→ is its inclination to the horizontal.

The complex three-dimensional nature of the kiln, with variations in the x, z and ϕ directions necessitates simplifications to enable a solution of the model equations. The bed height t_b is that corresponding to the one required for a bed with the same cross-sectional area and the same area exposed to the gas as in the actual kiln. It is reasonable to assume that the bed height remains constant in the burnout zone because char constitutes but a small fraction of the solids in this zone.

2.1.5 Hydrodynamic and dispersion in active layer of rotary kilns

This model is given by M.D. Heydenrych *et al.* A hydrodynamic model is prepared to predict its shape. A mass balance on particles moving within a rotary kiln gives the shape of the active layer, defined as that part of the bed where particles move past each other. Here the derivation is based on the assumption that there is a linear velocity gradient of particles in the direction perpendicular to the surface of the bed that is constant at any place on the bed surface. Published data was used to establish a relationship between this velocity gradient on the one hand, and bed fill and rotation speed on the other. A dispersion model was derived to predict the mass. transfer of gaseous reactant within the active layer. As void spaces are created and destroyed due to the action of particles moving over each other, mixing of gas occurs. A dispersion coefficient was derived, based on this gas mixing, and was found to be proportional to the velocity gradient and to the square of particle diameter. Applying these relationships to a 1-dimensional concentration gradient model gave a correlation for the mass transfer coefficient at the bed surface. This model does not correctly predict the proportionality of mass transfer with bed speed reported in the literature. It is concluded that another effect, probably the granular temperature of the particles, is important for modeling of dispersion and mass transfer in the active layer of rotary kilns.

Here he has explored the physical processes that occur within the active layer in order to model the depth and shape of the active layer, and to predict the dispersion that can be expected. With these models, it estimate concentration profiles and finally calculate the effective mass transfer coefficient (based on bed surface area) for the active layer for a given rotation speed, particle size and bed depth.

In most rotary kiln operations the chemical reactions in the bed require high temperature, for example cement kilns will require temperatures of approximately 1500^{0} C. The energy to raise the temperature and drive endothermic reactions is from the combustion of a range of fuels such as natural gas, coal and more and more alternative fuels. Heat transfer from the gas to the bed is complex and occurs from the gas to the bed surface and kiln wall to bed surface via conduction, convection, and Radiation.

The rotary kiln model being developed encompasses a general mass and energy balance over the process. The mass energy balance uses measured input and output; temperatures, pressures and mass flow (where possible) and gas composition at the kiln backend.

There are three different heat transfer mechanisms in the rotary kiln:

- Convection (from gas to bed and inner wall and outer wall to surroundings)
- Conduction (between bed and inner wall and inner and outer wall)
- Radiation (main heat transfer mechanism)

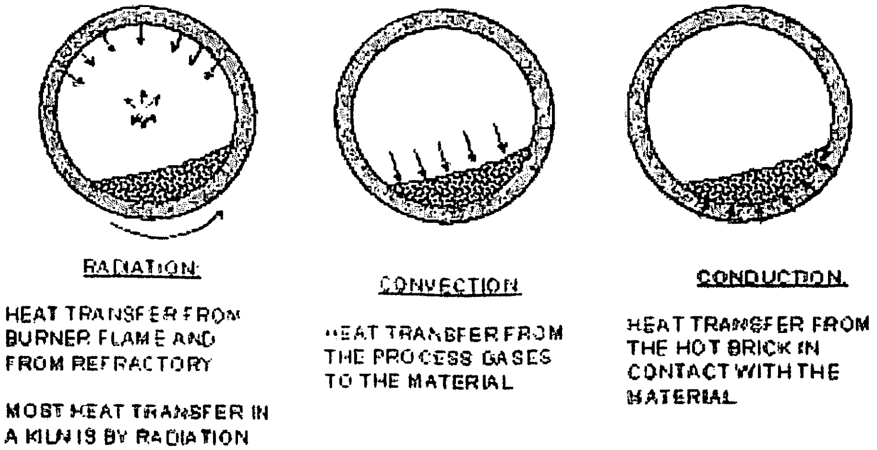


Figure 3.1 Radiation, Convection, and conduction in Rotary Kiln

Heat is transferred in a variety of ways. The most effective way of transferring heat is by radiation from the hot flame and combust ion gases. The second much smaller amount of energy radiation is brick radiation. The glowing hot brick transfers heat by radiation to the material. Hot brick also transfers heat by conduct ion to the underside of the bed charge. The last form of transfer is the exchange of temperature from the hot air to the material in convection.

Convection of air to material is entirely taking place in a preheater. In lime recovery kilns were fine material is in kiln, chain systems are also used for heat transfer.

3.1 Benefits of Incineration

Solid Wastes ----------------------→ Conversion Products
(solid, liquid, gas)

- Reduction in the volume and weight of waste
    - up to 90% of volume and 75% of weight
- Destruction of some wastes and detoxification of others
    - combustible carcinogens, toxic organic compounds, or biologically active materials that could affect sewage treatment works.
- Destruction of the organic component of biodegradable waste

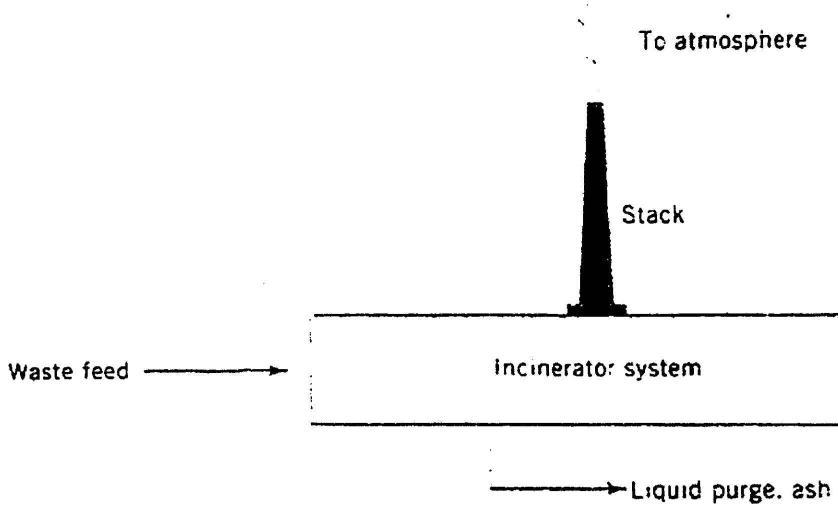
which when land filled directly generates landfill gas (LFG)

- The recovery of energy from organic wastes

3.2 Types of fuel used in rotary kiln

Kilns can be fired with natural gas, fuel oil, pulverized solid fuels, or a combination of all of these. It can also used waste fuel with have higher calorific value.

Schematic of an Incinerator System



3.3 Performance Standards

- Destruction and Removal Efficiency (DRE)
  - Sample waste stream is prepared ,noting principle organic hazardous constituents (POHCs) ,roughly 400 listed.

$$DRE = \frac{W_{in} - W_{out}}{W_{in}} \times 100$$

Win = mass feed rate in,

Wout = mass emission rate from stack of same material

  - Trial burn; selecting a few POHCs to burn and analyze
  - Must burn to DRE = 99.99% or greater
  - Must burn to DRE = 99.9999% for polychlorinated biphenyl (PCB)
- Particulate Emission Limits
  - Less than 0.18 g/m³ (dry) or more
- Products of Incomplete Combustion Emission Limits
  - CO levels
- Metal Emission Limits
  - Carcinogenic/Non-carcinogenic; adjusted stack height

- HCl and Cl Emission Limits
- Other Federal Regulations
    - Noise
    - SO_x
    - NOx
    - Dioxin/furan

3.4 Combustion Products

- Gas and Vapor
    - Ideally: CO_2, H_2O. O_2. N_2, and traces of SO_2
    - Reality: SOx, NOx.
        - Traces of Hg, Pb, As, Cd, dioxins, furans, and organic compounds
- Solid and Liquid
    - Combustion Residues
        - Bottom Ash
        - Fly Ash
        - Noncombusted Organic and Inorganic Material
        - Scrubber Sludge & Wastewater Treatment Plant Sludge

3.5 Equations Development

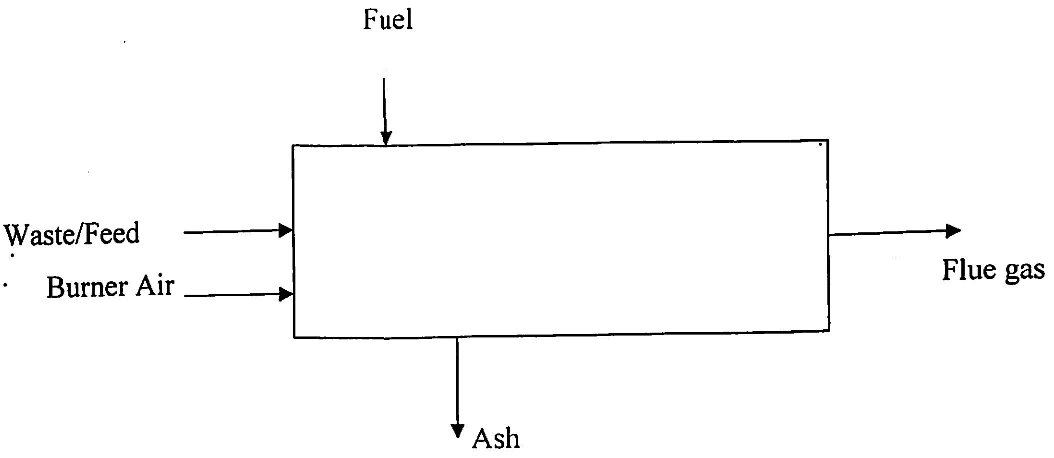


Figure 3.2 Rotary Kiln Incirerator

3.5.1 Mass Balance

Material In= Material Out

Material In = Waste In + Fuel In + Burner air

Material Out = Flue gas + Incinerated Ash

$$m_{waste \to feed} + m_{fuel} + m_{burner\ air} = m_{flue\ gas} + m_{incinerated\ ash} --(1)$$

3.5.2 Energy Balance

$$\dot{q}_h = \dot{m}\Delta H = Q\rho_g \Delta H$$
$$= Q\rho_g C_p (T - T_0) = \dot{m} C_p (T - T_0) ------(2)$$

Where,

$\dot{q}_h$ --------Heat Rate Required

Q -----------Gas Volume Flow Rate

ρ_g -------Gas Density

H ---------Enthalpy

C_p ---------Specific Heat

T_0 ----------Reference Temperature (25 °C or 60 °F)

3.5.3 Steady State Energy Balance

$$m_{waste}\Delta H_{waste} + m_{fuel}\Delta H_{fuel} + m_{burner\ air}\Delta H_{burner\ air} + m_{fuel}\Delta H_{combustion} +$$
$$X_{VOC} m_{VOC} \Delta H_{VOC\ Combustion} - q_{loss}$$
$$= m_{flue\ gas}\Delta H_{exhaut} + m_{incinerated\ ash}\Delta H_{ash} ----------------(3)$$

X--→ Fractional Conversion of VOC [volatile organic content (compound)]

Assume (1) the enthalpy functions of all streams are similar to that for air

$$\Delta H = C_p(T - T_0)$$

(2) the heat loss is a fraction of the heat input

$$q_{loss} = \left(m_{fuel}\Delta H_{combustion} + X_{VOC} m_{VOC} \Delta H_{VOC\ combustion}\right) \times f_{loss} \quad -(4)$$

3.5.4 Combining mass balance and heat loss relationship with energy balance

$$\left(\dot{m}_{waste} + \dot{m}_{fuel} + \dot{m}_{burner\ air}\right)\Delta H_{exhaust}$$
$$= \dot{m}_{waste}\Delta H_{waste} + \dot{m}_{fuel}\Delta H_{fuel} + \dot{m}_{burner\ air}\Delta H_{burner\ air}$$
$$+ \dot{m}_{fuel}\Delta H_{combustion} + X_{VOC}\dot{m}_{VOC}\Delta H_{VOC\ combustion}$$
$$-\left(\dot{m}_{fuel}\Delta H_{combustion} + X_{VOC}\dot{m}_{VOC}\Delta H_{VOC\ combustion}\right)f_{loss} \quad --(5)$$

Then group items by each material flow

$$\dot{m}_{fuel} = \begin{bmatrix} \dot{m}_{waste}(\Delta H_{exhaust} - \Delta H_{waste}) + \dot{m}_{burnerair}(\Delta H_{exhaust} - \Delta H_{burnerair}) \\ - X_{VOC}(1 - f_{loss})\dot{m}_{VOC}\Delta H_{VOC\,combustion} \end{bmatrix}$$

$$/\left[\Delta H_{combustion}(1 - f_{loss}) - (\Delta H_{exhaust} - \Delta H_{fuel})\right] ----(6)$$

3.5.5 Combustion Kinetics

$$\frac{dC_A}{dt} = -kC_A^n ---------- (7)$$

Where, C_A = concentration of pollutant A

k = Kinetic Rate Constant

n = reaction order

If pollutant concentration is much less than O_2 concentration, n can be assumed to be 1.

$$\frac{C_A}{C_{A_o}} = \exp(-kt) --------- (8)$$

Equation of rate constant

$$k = A\exp\left(-E_{act}/RT\right) ----------------- (9)$$

Where,

E_{act} = Activation Energy (cal/mol)

R = Gas Constant (1.987 cal/gmole K)

3.5.6 Heat of Combustion

Higher Heating Value (HHV) = Lower Heating Value (LHV) + Latent Heat of Water

1 BTU/lb = 2.326 KJ/kg

3.5.7 Sizing the Incinerator

- Incinerator Diameter - $D_I = \sqrt{\frac{4Q_{exhaust}}{\pi v_T}}$ --- (10)
- Length of the Incinerator $L = v_T \tau_r$

Where,

$Q_{exhaust}$ = exhaust flow rate

v_T = gas velocity in the incinerator (20 ~ 40 ft/s)

t_r: residence time (0.2 ~ 2.0 s)

Length/diameter = 2 ~ 3

3.5.8 Heat Balance for Combustion Fuel

$$Q_f = Q_g + Q_l + Q_p \text{ ----------------- } (11)$$

Where,

Q_f = Heat generated by combusting the fuel.

Q_g = Heat going to the load.

Q_l = Heat lost through wall.

Q_p = Heat Carried out by exhaust products.

3.6 Combustion system in Rotary kiln

The objective of most waste incineration processes is to destroy or burn any of the organic materials in the waste, leaving only an inert residue. The waste combustion system consists of the following components:

- Waste preparation and feeding,
- Combustion equipment,
- Heat recovery equipment,
- Air pollution control equipment,
- Ash/solid residue stabilization and disposal.

Combustion is the conversion of fossil fuel into chemical compounds (or products) by combining it with an oxidizer, usually oxygen in air. The combustion process is an exothermic chemical reaction, that is, a reaction that releases heat energy as it occurs.

Fuel + Oxidizer -----→ Products of combustion + Energy

Here the fuel and oxidizer are the reactants, that is, the substances that were present before the reaction took place. The relation indicates that the reactant produce combustion products and energy but as it known in the fire triangle, their must also be an ignition source for it to proceed. The amount of heat released during combustion depends upon types of fuel.

There are four components that are important in the transfer of thermal energy from a combustion process to some type of heat load (see Figure 3.3). One component is the burner, which combusts the fuel with an oxidizer to release heat. Another component is the load itself, which can greatly affect how the heat is transferred from the flame.

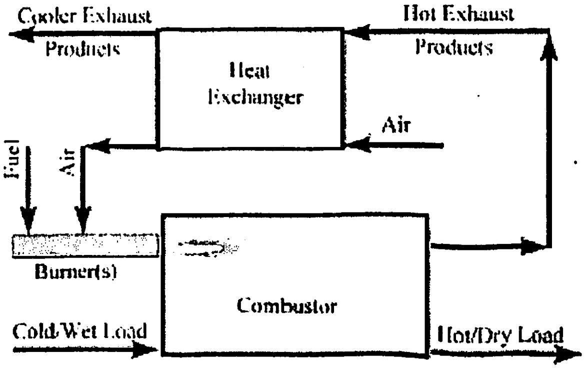


Figure 3.3 Schematic of the major components in a combustion system.

Gas recirculation

A common technique used in combustion systems is to design the burner to induce furnace gases to be drawn into the burner to dilute the flame, usually referred to as furnace gas recirculation. Although the furnace gases are hot, they are still much cooler than the flame itself. This dilution may accomplish several purposes. One is to minimize NOx emissions by reducing the peak temperatures in the flame. However, furnace gas recirculation may be preferred to FIGR because no external high-temperature ductwork or fans are needed to bring the product gases into the flame zone. Another reason to use furnace gas recirculation may be to increase the convective heating from the flame because of the added gas volume and momentum.

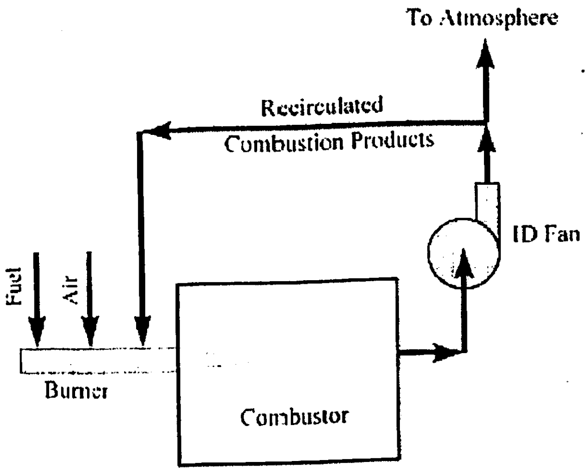


Figure 3.4 Schematic of flue gas recirculation.

3.7 Modeling Approach for Combustion System

A complete combustion system may include a wide range of physical processes that are often highly interactive and interdependent. A rotary Kiln combustor may include.

- Turbulent fluid dynamics in the flame with laminar fluid dynamics in the bulk of the combustor.
- Multidimensional flows, which could include swirl
- Multiple phases that could include gases, liquids, and solids, depending on the fuel composition
- Very high temperature, velocity, and species gradients in the flame region with much lower gradients in the bulk of the combustor
- Large material property variations caused by the wide range of temperatures, species, and solids present in the system
- Multiple modes of heat transfer, especially radiation that is highly nonlinear and may include wavelength dependence
- Complex chemistry involving numerous reactions and many species, most of which are in trace amounts
- Porous media
- Catalytic chemical reactions in some limited applications
- Complex, nonsymmetrical furnace geometries

- Multiple flame zones produced by burners that may be operated at different conditions and whose flames interact with each other
- A heat load that may be moving and interacting with the combustion space above it in a nonlinear manner
- A heat load that may produce volatile species during the heating process
- A heat load whose properties may vary greatly with temperature, physical state, and even wavelength for radiation
- A transient heating and melting process that may include discrete material additions and withdrawals.

- The important aspects of the problem statement for industrial combustion modeling in rotary kiln
  - Geometry of the combustion chamber
  - Fuel and air input conditions
  - Thermal boundary conditions
  - Thermodynamic, transport, radiative, and chemical-kinetic properties, and the desired outputs of models
  - Velocity, temperature, composition, etc. throughout the chamber
  - Heat flux and temperature at the wall

3.8 Stoichiometric Combustion Calculation

The efficiency of rotary kiln incinerator depends on the efficiency of the combustion system. The amount of air required for complete combustion of the fuel depends on the elemental constituents of the fuel that is Carbon, Hydrogen, and Sulphur etc. This amount of air is called stoichiometric air. For ideal combustion process for burning one kg of a typical fuel oil containing 86% Carbon, 12% Hydrogen, 2% Sulphur, theoretically required quantity of air is 14.1 kg. This is the minimum air that would be required if mixing of fuel and air by the burner and combustion is perfect. The combustion products are primarily Carbon Dioxide (CO_2), water vapor (H_2O) and Sulphur Dioxide (SO_2), which pass through the chimney along with the Nitrogen (N_2) in the air.

After surrendering useful heat in the heat absorption area of a furnace or boiler, the combustion products or fuel gases leave the system through the chimney, carrying away a significant quantity of heat with them.

3.8.1 Mass Balance

$$m_{waste} + m_{fuel} + m_{burner\ air} = m_{flue\ gas} + m_{incinerated\ ash} \quad --(1)$$

m_{waste} = 56250 kg/hr.

m_{fuel} = 5 Kg/hr

$m_{burner\ air}$ = 2189 kg/hr

$m_{incinerated\ ash}$ = 1470 kg/hr.

These values has taken form the working plant condition

From equation (1)

$m_{flue\ gas}$ = 56974 kg/hr.

3.8.2 Steady State Energy Balance

Specific heat of the following component

C_p	**KJ/Kg-^{0}K**
Waste	**1.5**
Fuel oil	**1.88**
Air	**1.0**
Ash	**1.3**
Flue gas	**5.373**

$$m_{waste} \times \Delta H + m_{fuel} \times \Delta H + m_{air} \times \Delta H + m_{fuel} \times \Delta H_{Combustion} + m_{waste} \times \Delta H_{Combustion} - q_{loss}$$

$$= m_{flue} \Delta H + m_{ash} \times \Delta H$$

$$q_{loss} = (m_{waste} \times \Delta H + m_{fuel} \times \Delta H)) \times f$$

$f = 5$ % , $\Delta H_{Combustion}$ =25 KJ/gm(for fuel)

$\Delta H_{Combustion}$ =2.91 KJ/gm (for waste)

$$q_{loss} = (56250 \times 1.5 \times (T_1 - 25) + 5 \times 1.88 \times (T_1 - 25)) \times .05$$

T_1 = 960 °C (Inlet Temperature)

T_2 = Outlet Temperature

$$q_{loss} = (56250 \times 1.5 \times (960 - 25) + 5 \times 1.88 \times (960 - 25)) \times .05$$

q_{loss} = 3944970.7 J/hr

q_{loss} = 3.944 MJ/hr.

1 Calorie = 4.1868 J

q_{loss} = 0.9422 Mcal/hr.

$$\frac{1}{4.1868}\begin{bmatrix} 56250 \times 1.5 \times (960 - 25) + 5 \times 1.88 \times (960 - 25) + \\ 2189 \times 1 \times (960 - 25) + 5 \times 25 \times 10^3 + 56250 \times 2.91 \times 10^3 \end{bmatrix} \times 10^{-3} - 0.9422$$

$$= \frac{1}{4.1868}\left[56974 \times 5.373 \times (T_2 - 25) + 1470 \times 1.3 \times (T_2 - 25)\right] \times 10^{-3}$$

T_2 = 819.57 °C

$$T_2 \approx 820 \ ^oC$$

Calculation of Stoichiometric Air

The sample of waste and fuel oil mixture gives the specification from the lab analysis.

Constituents	% By Weight
Carbon	85.9
Hydrogen	12
Oxygen	0.7
Nitrogen	0.5
Sulphur	0.5
H_2O	0.35
Ash	0.05

Calculation for Requirement of Theoretical Amount of Air for fuel and waste

Now, by considering 56255 kg of mixture . The chemical reactions are:

Element	Molecular Weight
C	12
O_2	32
H_2	2
S	32
N_2	28
CO_2	44
SO_2	64
H_2O	18

$$C + O_2 \rightarrow CO_2$$

$$H_2 + \frac{1}{2}O_2 \rightarrow H_2O$$

$$S + O_2 \rightarrow SO_2$$

Constituents of mixture

$C + O_2 \text{-----}\rightarrow CO_2$

$12 + 32 \text{----}\rightarrow 44$

12 Kg of C requires 32 Kg of O_2 to form 44 Kg of CO_2

Therefore 1 Kg of carbons requires 32/12 Kg i.e 2.67 kg of O_2

Now, 85.9 Kg Carbon is present in mixture from lab analysis

So, $(85.9)C+(85.9*2.67)O_2 \text{---}\rightarrow 314.97\ CO_2$

Similarly,

$2H_2+O_2 \text{--------}\rightarrow 2H_2O$

$4+32 \text{-------}\rightarrow 36$

4 Kg of H_2 is requires 32 Kg of Oxygen to form 36 kg of water

Therefore 1 kg of H_2 requires 32/4 kg i.e 8 kg of O_2

So, $(12)H_2 + (12*8)\ O_2 \text{--------}\rightarrow (12*9)H_2O$

$S + O_2 \text{--------}\rightarrow SO_2$

$32 + 32 \text{-------}\rightarrow 64$

32 kg of sulphur requires 32 kg of oxygen to form 64 kg of sulphur dioxide

Therefore 1 kg of sulphur requires 32/32 kg i.e 1 kg of oxygen

$(0.5)\ S + (0.5*1)\ O_2 \text{----------}\rightarrow 1.0\ SO_2$

Now,

Total oxygen required (229.07+96+0.5) = 325.57 Kg.

Oxygen already present in mixture (Given) = 0.7

Additional Oxygen required = 325.57 – 0.7 = 324.87 kg

Therefore quantity of dry air required.(air contains 23 % Oxygen by wt.) = 324.87/0.23

= 1412.45 kg of air

Theoretical air required = (1412.45)/ 56255 kg = 0.02510 (kg) of air / kg of mixture

Calculation of theoretical CO_2 content in flue gases

Nitrogen in flue gas = 1412.45-324.87

= 1087.58 Kg

Theoretical CO_2% in dry flue gas by volume is calculated as below :

Moles of CO_2 in flue gas = (314.97) / 44 = 7.16

Moles of N_2 in flue gas = (1087.58) / 28 = 38.84

Moles of SO_2 in flue gas = 1/64 = 0.016

$$Theoretical\ CO_2\%by\ Volume = \frac{Moles\ CO_2}{Total\ Moles(dry)} \times 100$$

$$= \frac{7.16}{7.16 + 38.84 + 0.016} \times 100$$

$$= 15.5\%$$

Calculation of constituents of flue gas with excess air

% CO_2 measured in flue gas = 10 % (measured)

$$\%Exess\ air = \left(\frac{Theoretical\ CO_2\%}{Actual\ CO_2\%} - 1 \right) \times 100$$

$$\%Excess\ air = \left(\frac{15.5}{10} - 1 \right) \times 100 = 55\%$$

Theoretical air required for 56255 kg of mixture burnt = 1412.45 Kg

Total Quantity of air supply required with 55 % excess air = 1412.45 * 1.55

= 2189.30 Kg

Excess air quantity = 2189.30 – 1412.45 = 776.85 Kg.

O_2 = 776.85 * 0.23 = 178.68

N_2 = 776.85 – 178.68 = 598.17 Kg.

Final constitution of flue gas with 55% excess air for every 56255 kg of mixture.

CO_2 = 314.97 Kg

H_2O = 108.00 Kg

SO_2 = 1 Kg

O_2 = 178.68 Kg

N_2 = 1087.58 + 598.17

= 1685.75 Kg.

Calculation of Theoretical CO_2% in Dry Flue Gas By Volume

Moles of CO_2 in flue gas = 314.97/44 = 7.16

Moles of SO_2 in flue gas = 1/64 = 0.016

Moles of O_2 in flue gas = 178.68 / 32 = 5.58

Moles of N_2 in flue gas = 1685.75 / 28 = 60.20

$$Theoretical\ CO_2\%by\ Volume = \frac{Moles\ CO_2}{Total\ Moles(dry)} \times 100$$

$$= \frac{7.16}{7.16 + 0.016 + 5.58 + 60.20} \times 100$$

$$= \frac{7.16}{72.956} \times 100$$

$$\approx 10\%$$

$$Theoretical\ O_2\%by\,volume = \frac{5.58}{72.956} \times 100 = 7.6\%$$

Optimizing Excess Air and Combustion

For complete combustion of every one kg of fuel oil and waste (Mixture) 0.02510 kg of air is needed. In practice, mixing is never perfect, a certain amount of excess air is needed to complete combustion and ensure that release of the entire heat contained in fuel oil. If too much air than what is required for completing combustion were allowed to enter, additional heat would be lost in heating the surplus air to the chimney temperature. This would result in increased stack losses. Less air would lead to the incomplete combustion and smoke. Hence, there is an optimum excess air level for each type of waste.

Control of Air and Analysis of Flue Gas

Thus in actual practice, the amount of combustion air required will be much higher than optimally needed. Therefore some of the air gets heated in the furnace boiler and leaves through the stack without participating in the combustion.

Chemical analysis of the gases is an objective method that helps in achieving finer air control. By measuring carbon dioxide (CO_2) or oxygen (O_2) in flue gases by continuous recording instruments or Orsat apparatus or portable fyrite, the excess air level as well as stack losses can be estimated with the graph as shown in Figure 3.5 and Figure 3.6. The excess air to be supplied depends on the type of fuel and the firing system. For optimum combustion of fuel oil, the CO_2 or O_2 in flue gases should be maintained at 14 -15% in case of CO_2 and 2-3% in case of O_2.

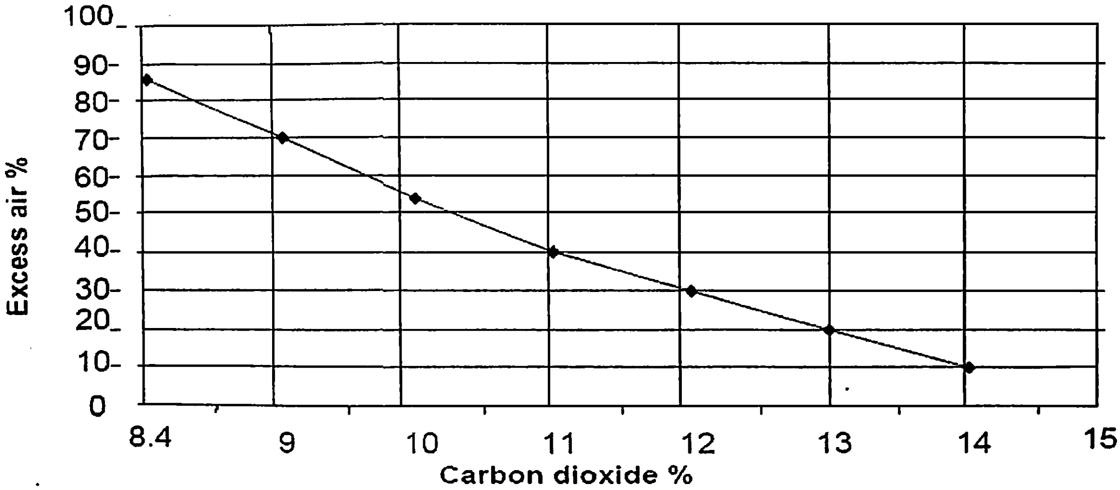


Figure3.5 Relation between CO2 and Excess Air for Fuel Oil

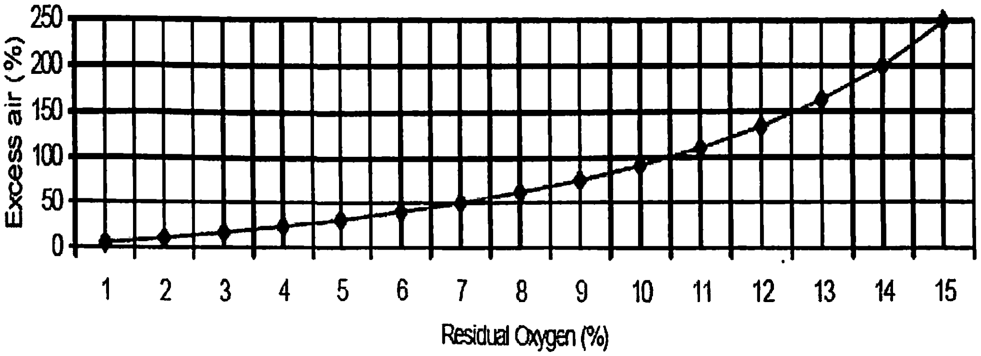


Figure 3.6 Relations between Residual Oxygen and Excess Air

One table has been created with the working plant condition; this gives Temperature and Heat Profile in rotary kiln (Primary Combustion Chamber) and Secondary combustion chamber. It includes the monitoring and analysis summary.

4.1 Temperature and Heat Profile data sheet for Rotary Kiln Incinerator

S.N	Time (Hrs)	Temp. of rotary		Rotary furnace				Temperature Sec	Secondary		Rotary	Secondary	Total Heat Input	Stack Temp.
		T1	T2	P1	P2	P3	P4	T3	P5	P6	HEAT INPUT	HEAT INPUT		T4
		Front	Rear					Centre top						Inlet of ID fan
1	10	960	830	405	300	20	150	1240	400	0	3.5	1.9	5.4	40
2	11	955	835	399	290	20	100	1242	350	0	3.2	1.8	5	43
3	12	950	833	380	280	20	125	1248	330	0	3.1	1.7	4.8	41
4	1	958	838	340	310	20	175	1250	320	0	3.2	1.6	4.8	38
5	2	948	840	320	260	20	200	1240	350	0	3.05	1.2	4.25	35
6	3	945	845	310	220	20	150	1255	310	0	2.99	1.5	4.49	32
7	4	940	842	299	250	20	175	1260	300	0	2.95	1.3	4.29	30
8	5	943	848	280	230	20	225	1258	280	0	2.99	1.4	4.39	33
9	6	947	855	270	200	20	175	1265	260	0	2.8	1.2	4	35
10	7	940	858	260	240	20	225	1270	255	0	2.85	1	3.85	37
11	8	942	860	250	220	20	250	1275	250	0	2.91	0.8	3.71	35
	Total			3513	2800	220	1950		3405	0	33.54	15.4	48.98	
	Average	948	844	319.4	254.5	20	177.3	1254.8	309.5	0	3.04	1.4	4.5	36.3

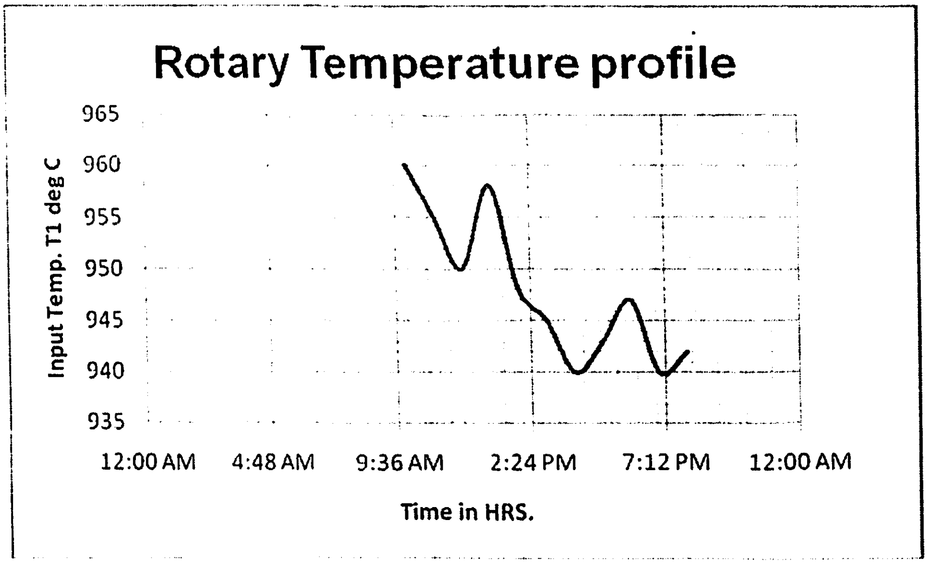
Note:

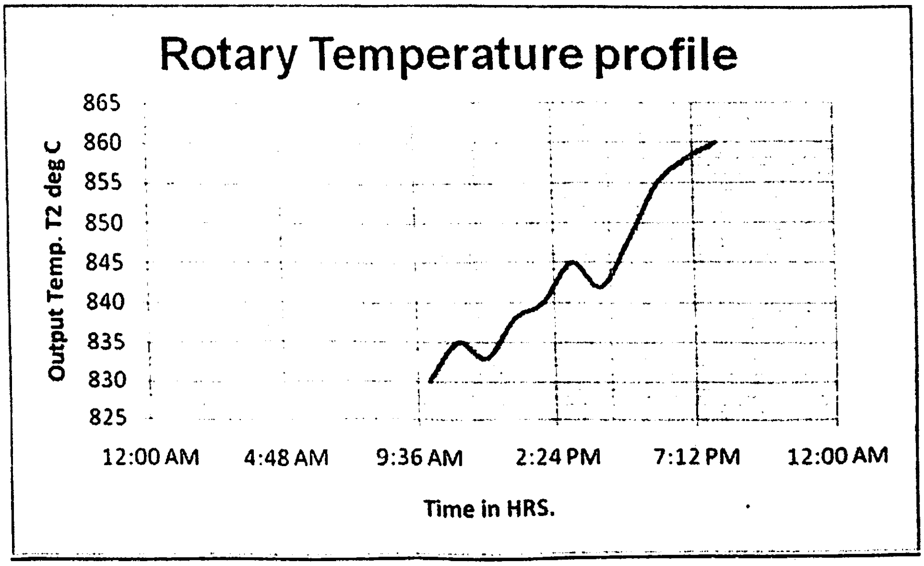
1. Temperature in Deg °C
2. Calorific Value in KCal/KG
3. Heat Load in MKCal/Hr.
4. Charging Feed Rate in Liter Per hour
    - P1, P2---→Liquid Charging
    - P3,P6---→LDO Charging
    - P5-----→High C.V Charging
5. Solid Charging in KG/Hr.(P4 point), (1 Bag = 25-30 KG)
6. Moisture & LOI in Wt. Percentage

4.2 Monitoring & Analysis Summary

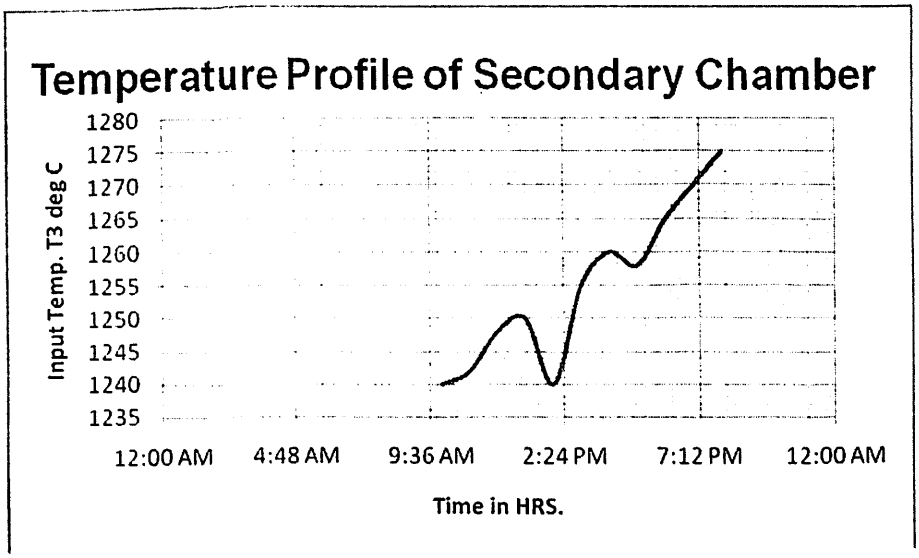
Total Solid Incineration(P4)	1950	Kg
Total Liquid Incineration(P1+P2+P3+P5)	9938	Kg
Total Waste Incineration	11888	Kg
Average Feed Rate		
Total Solid Incineration	177.3	Kg/Hr.
Total Liquid Incineration	903.4	Kg/Hr.
Total Waste Incineration	1080.7	Kg/Hr.
Average Heat Load to Rotary	3.04	MKCal/Hr.
Average Heat Load to Secondary	1.4	MKCal/Hr.
Total Average Heat Load of Plant	4.44	MKCal/Hr.

4.3 Rotary Temperature Profile



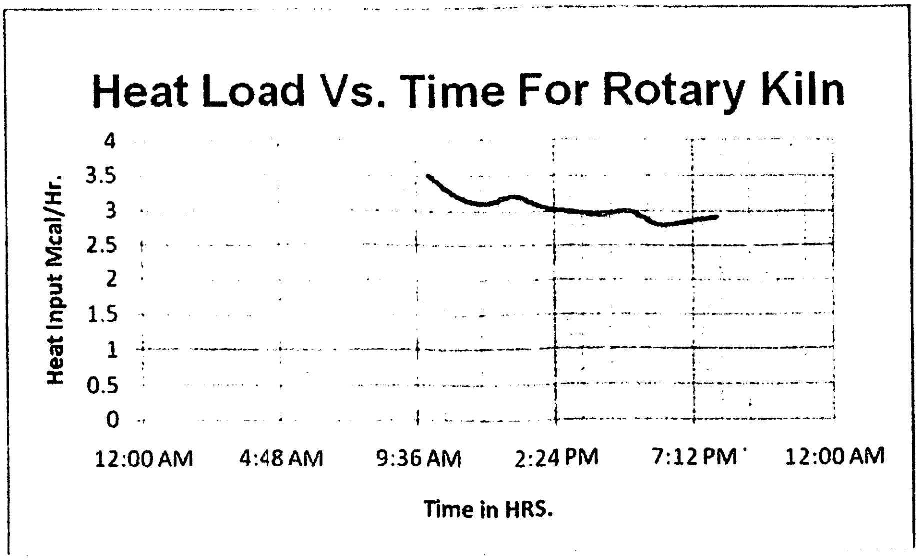


4.4 Secondary Temperature Profile

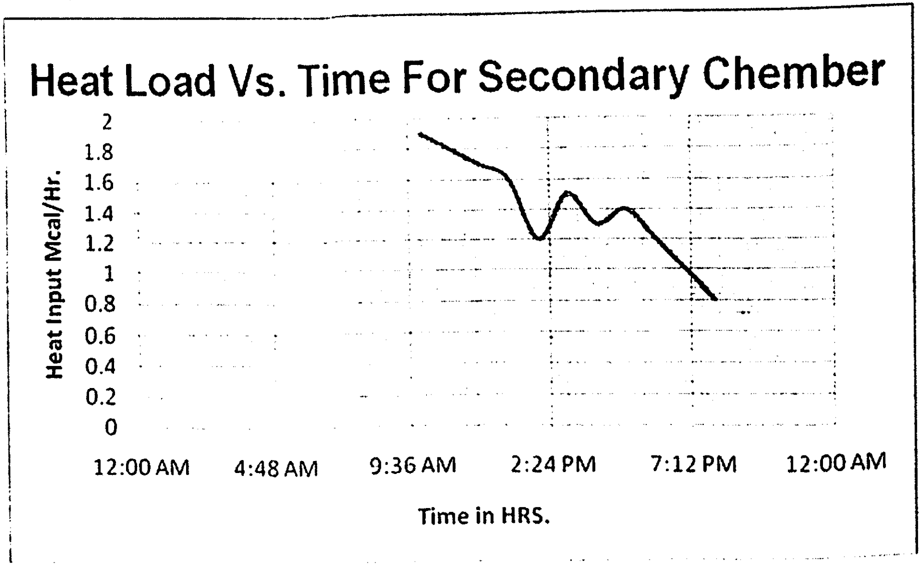


4.5 Heat Load Vs Temperature

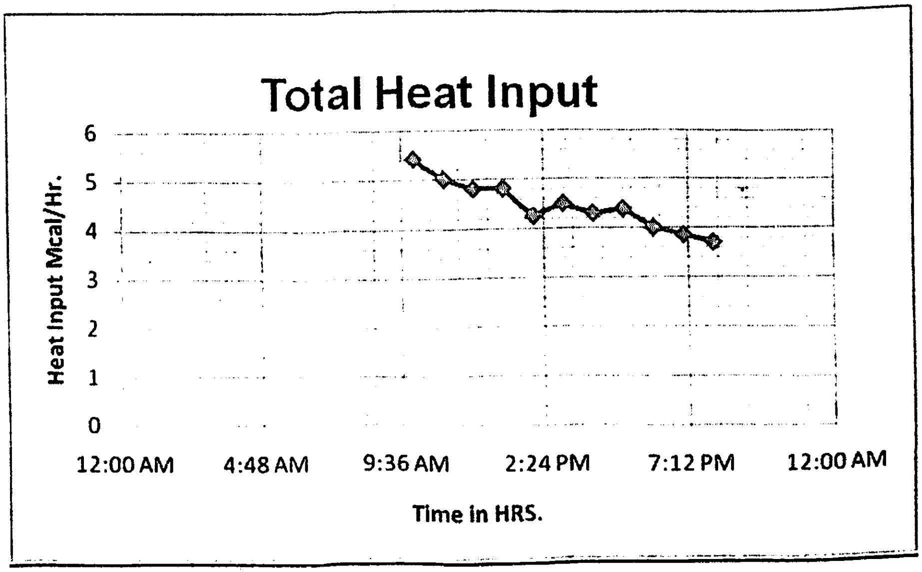
a) Rotary kiln



b) Secondary Chamber



c) Total Heat Input



Details of table provides the idea of performance evaluation of rotary kiln, from this we can see the temperatures profiles during the operation, which gives the overall idea of rotary kiln performance. The combustion temperature should be between 850-12000 ^{0}C for the complete combustion of the waste. The temperature between 250^{0}C – 350^{0}C is avoided in the quenching process due to dioxins formation.

These overall results give the following details.

1. The rotary kiln furnace is optimum for the treatment of waste plastics, wood chippings, paper cuttings, sludge, waste oil, waste liquid, etc.
2. It is possible to thermally decompose and burn plastic wastes, and perform low-NO_x operation.
3. Because the rotary kiln furnace is used, pre-treatment is very simple and easy.
4. One furnace can treat materials extensively, ranging from solid matter and liquid matter to gaseous matter.
5. Because the residence time in the furnace is relatively long, about 30 to 60 minutes, load variations on the feed side are absorbed, and thus, stable combustion is possible.

These all results give the overall idea about the performance of rotary kilns. These kilns are ubiquitous fixtures of the metallurgical and chemical process industries. Despite challenges newer and more specialized gas-solid reactors, they continue to find applications in the drying, heating (or cooling), calcining, reducing, roasting and sintering of a variety of materials. It can handle feed stock with broad particle size distributions or whose physical change significantly during processing, while the long residence time of material within the kilns promotes uniform product quality. In addition, dirty fuel often is utilized without serious product contamination, and multiple fuel capability is possible. Paradoxically, this versatility, which has in the past ensured the survival of the rotary kiln, now threatens its future. Because a thorough understanding of processes occurring in the rotary kilns has not been a prerequisite for their apparently satisfactory operation, research has not progressed apace with competing, less tolerant, reactors. Until all the internal process are understood and becomes predictable, rotary kilns will remain in the position of operating bellow their optimal performance in an increasingly sophisticated marketplace.

This thesis gives the overall idea about the performance of rotary kiln. Mass and Energy equation has been made across the rotary kiln which gives the parametric relation between feed and product. These all types of equations include the molecular level studies about Rotary kiln. The mass and enery balance has been checked from the plant data. It also includes the combustion system of the rotary kiln, where the approach of modeling has been given for the combustion system. Stoichiometric calculation has been done for monitoring the combustion system which gives the optimum air and other combustion constituents required for the complete combustion of the waste. The complete observed values in tabular form give the idea of the performance of rotary kiln incinerator. These equations predict important aspects of its overall performance and several trends involving parametric variations in its operation. These analysis will prove helpful in the analysis and design of waste-to-energy facilities employing this technology and when further validated using literature and other experimental data. It will provide an exciting tool for tuning the operation of existing kilns, and to provide a systematic basis for the efficient design of new kilns.

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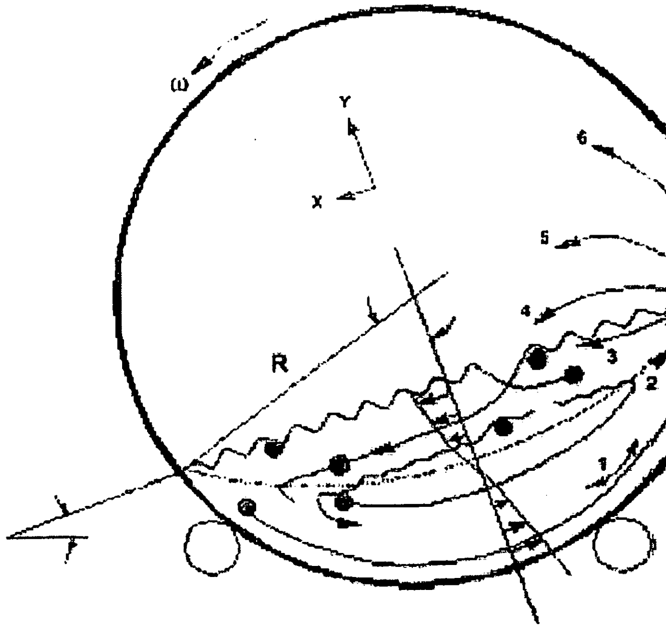
Appendix

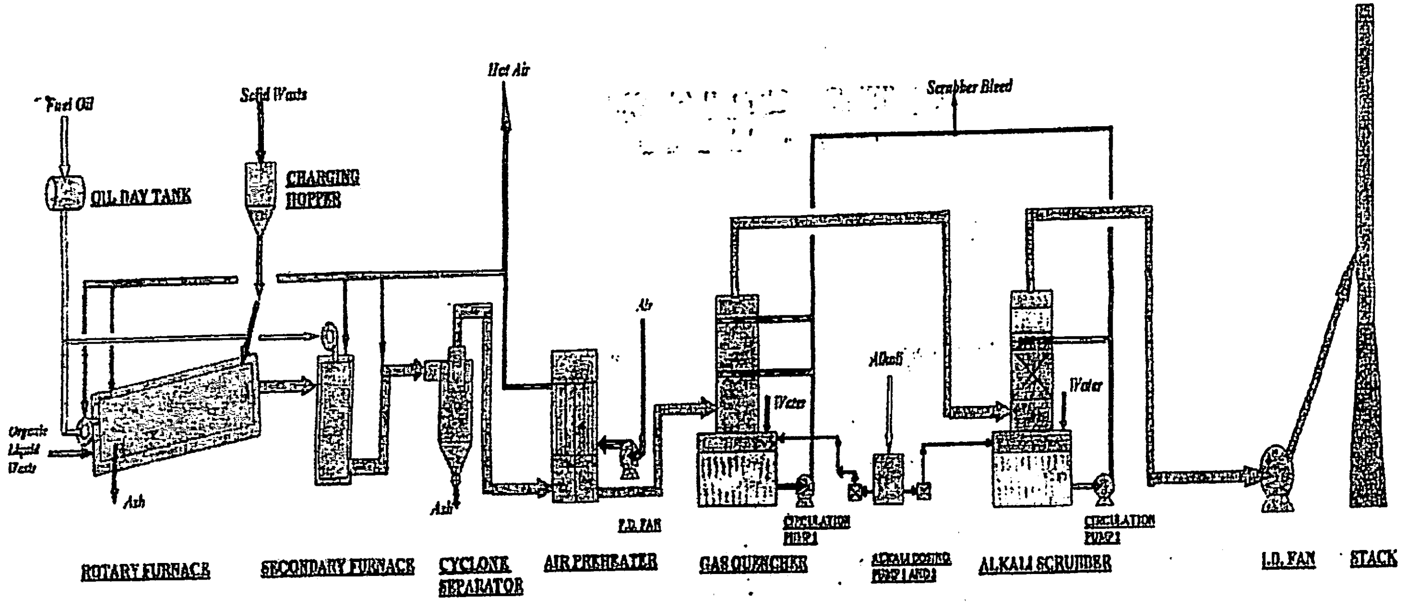
Schematic of a cross-sectional view of granular flow in a rotary kiln, including the bed behavior at 12% loading.



Mode	$Fr = \frac{\omega^2 R}{g}$
Slipping	$Fr<1\times10^{-5}$
Slumping	$1\times10^{-5}<Fr<0.3\times10^{-3}$
Rolling	$0.5\times10^{-3}<0.2\times10^{-1}$
Cascading	$0.4\times10^{-1}<Fr<0.8\times10^{-1}$
Cataracting	$0.9\times10^{--1}<Fr<1$
Centrifuging	$Fr \geq 1$

GUJARAT ENVIRO PROTECTION AND INFRASTRUCTURE LTD, SURAT

EMS
ISO 14001



Capacity:

Solid Waste: 700 kg/hr
Liquid Waste: 1200 kg/hr

SOLID AND LIQUID WASTE INCINERATOR
(TWIN CHAMBER ROTARY KILN TYPE)