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Performance Analysis of 250 MW Lignite Fired Circulating Fluidized Bed Combustion Boiler

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Abstract

The traditional grate fuel firing systems have got their own limitations and are techno-economically unviable to meet the challenges of the future. Fluidized bed combustion has emerged as a viable alternative and has significant advantages over conventional firing system and offers multiple benefits which include compact boiler design, fuel flexibility, and higher combustion efficiency and reduced emission of noxious pollutants such as SOx and NOx. Lignite particles of 300 microns size were used for analysis for a 250 MW Circulating Fluidized bed Combustion (CFBC) boiler. The fluid bed temperature was taken in the range of 800-950 degree centigrade. The proximate and ultimate analysis data were obtained. Based on the heat loss or indirect method the boiler efficiency was estimated and maximum heat loss was due to moisture content in the fuel.. The simulation results show that particle size plays a major role in the performance of CFBC boiler.

Keywords: Fluidized bed combustion, proximate and ultimate analysis, CFBC

1. INTRODUCTION

A gas solid fluidized bed is obtained by passing gas upwards through a bed of particles supported on a distributor. When the velocity exceeds the minimum fluidization velocity the fluid solid assembly behaves like a liquid. Pressure increases linearly with the distance below the surface. The lighter objects float and the denser objects sink and wave motion is observed. The pressure drop over a fluidized bed is much smaller. The gas bubbles continually moves the solids around shearing it and exposing it to the gas.

The behavior of most gas solid fluidized beds is dominated by the rising gas voids conveniently termed bubbles which characterize these systems. In analyzing the behavior of bubbling fluidized beds it is essential to distinguish between the bubble or lean phase i.e. the gas voids containing virtually no bed particles and the particulate phase also known as dense phase consists of particles fluidized by interstitial gas.

A bubbling bed can be defined as a bed in which the bubble phase is dispersed and the particulate phase is continuous. The rising bubbles cause motion of the particulate phase which is the main source of solids mixing in bubbling beds. This particle motion in turn causes temperature uniformity and high combustor to surface heat transfer coefficients. The Pressure drop of fluidized bed as compared to fixed bed is small. The fluidized bed includes particles of mean sizes ranging from 15 microns to 6 mm, bed diameter ranging from 0.1 to 13 m and gas velocities from 0.01 m/s to 10 m/s.

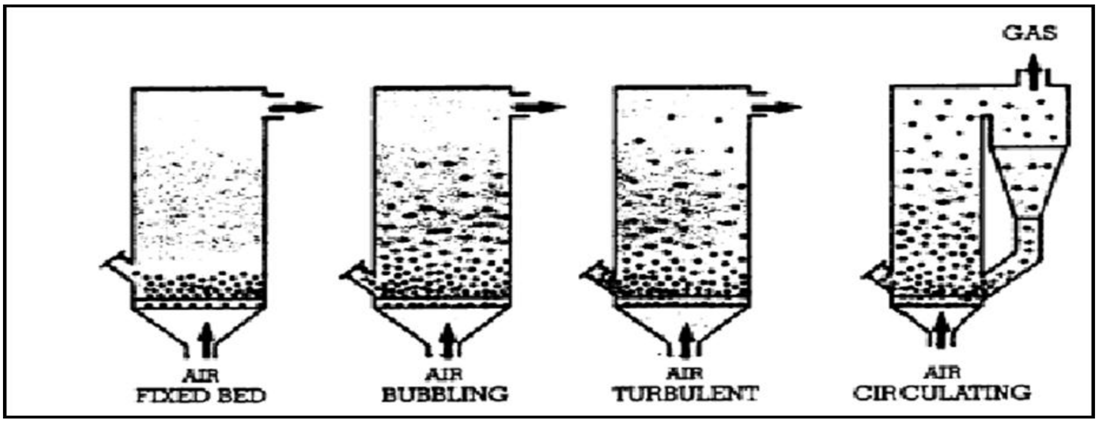


Fig.1 Regimes of fluidization

2. LITERATURE REVIEW

Geldart (1973) measured the transition velocity between the flow regimes and the particle entrainment rate. The entrainment rate is found to increase with the gas velocity and static bed height. Experiments were conducted for large scale combustors.

Wen et al (1967) analysed the gas/particle heat transfer involving conduction and convection. Uniform temperature was maintained in the bed. The change in temperature of the particle was measured as it came in equilibrium with the bed. Radiant heat transfer was considered small.

Botterill et al (1967) studied the wall heat transfer coefficient in a circulating fluidized bed which is due to conduction of particles falling along the walls. Heat transfer coefficient is larger for smaller walls. Heat transfer is related with the bed dynamics.

Levenspiel et al (1954) predicted the overall heat transfer coefficient from expressions involving modified Nusselt and Reynolds number. Simple expressions for gas film thickness were derived.

3. METHODOLOGY

From a detailed study of the literature and based on the inference from each study the methodology of the energy analysis was formulated. The operational parameters were identified to study the operational behaviour of the thermal system. Based on the data collection combustion, hydrodynamic and heat transfer analysis were carried out from which the overall efficiency of the boiler was found out. Simulation was performed using the ANSYS FLUENT software.

3.1 Flow diagram in a boiler

A boiler is a thermal system in which water is heated to obtain superheated steam which in turn is used to generate power by driving the turbo generator. The hot flue gases are left to the atmosphere via the stack. The combustion process in a boiler can be represented in the form of energy flow diagram. This shows graphically how the heat energy in the fuel is utilized well and the losses that can occur.

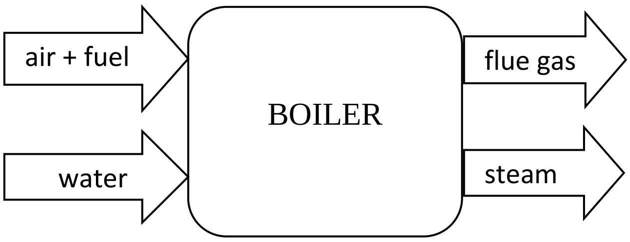


Fig 2. Flow diagram in a boiler

Combustion refers to the rapid oxidation of the fuel accompanied by generation of large amount of heat energy. Complete combustion is achieved by supply of adequate amount of air. The objective is to release all the energy present in the fuel which is achieved by controlling the temperature, turbulence and time.

3.2 Data collection

Table 1. Fuel specification and operational parameters

SL. NO	DATA	DESCRIPTION
1	Fuel	Lignite
2	Gross calorific value (Kcal / kg)	2650
3	Combustor type	Circulating Fluidized Bed
4	Ambient temperature (^{0}C)	32
5	Main steam temperature (^{0} C)	540
6	Main steam pressure (bar)	172
7	Main steam flow (tonnes/ hour)	845

Table 2. Elemental composition of the fuel

ELEMENT	% COMPOSITION BY MASS
Carbon (C)	27.50
Hydrogen (H_2)	2.20
Oxygen (O_2)	10.40
Nitrogen (N_2)	0.20
Sulphur (S)	0.70
Moisture	50.50
Ash	8.50

The above table shows that about 50% of the fuel contains moisture. Hence loss due to moisture in the fuel would be more.

Table 3. Fan data

FAN	NUMBER	FLOW PER FAN (m^3/s)	PRESSURE (mbar)	TEMPERATURE (^0C)
Primary air (PA) fan	2	82.03	310	45
Secondary air (SA) fan	2	83.80	150	45
Induced draft (ID) fan	2	318.3	48	146

Primary air fan is used to remove the moisture content in the fuel. Secondary air fan provides the combustion air and fluidizing air. Induced draft fan sucks the air and flue gas and expels them through the stack to the atmosphere. About 40% is fluidizing air.

Table 4. Blower data

BLOWER	NUMBER	FLOW PER BLOWER (m^3/s)	PRESSURE (mbar)	TEMPERATURE (^0C)
Sealpot	4+1	2552	400	45
Empty chamber	4+1	2388	500	45
Bundle chamber	4+1	19500	800	45

Exit chamber	1+1	6500	250	45
Seal and purge	1+1	5062	950	45
Ash cooler	2	6215	350	45

There are five types of blower namely Sealpot, Empty chamber, Bundle chamber, Exit chamber, Seal and purge, Ash cooler blower. The data corresponding to each blower is shown. Blowers are meant for intermediate pressure applications.

4. PERFORMANCE ANALYSIS

Efficiency of a thermal system reduces with time due to improper operation and maintenance, incomplete combustion and heat transfer. A heat balance helps to identify the avoidable and unavoidable losses and do the corrective action. Hence performance assessment is a prerequisite for energy conservation whose objective is to improve the energy efficiency.

4.1. The heat loss method

Heat losses that occur in a boiler can be controlled so that system efficiency is increased. Losses are unavoidable but energy can be recovered in the form of heat by use of suitable technology. The efficiency is arrived by subtracting all the heat losses from hundred. The various heat loses that occur in a boiler are heat loss due to dry flue gas, moisture in fuel, evaporation of water, moisture in air, incomplete combustion, radiation and convection losses (R & C losses).

$$\eta = 100 - \sum Losses + \sum credits \tag{1}$$

4.2. Air requirement

The total airflow is a combination of combustion air and infiltration air. Combustion air is used to burn the fuel which includes secondary air and primary air. Leakage of air into the boiler is known as infiltration. Theoretical air requirement can be obtained from the stoichiometric calculations.

$$m_{theoritical\ air} = \frac{100}{23}\left(\frac{8}{3}(27.5) + 8\left(2.2 - \frac{10.4}{8}\right) + 0.7\right) = \frac{353}{100} = 3.53\ kg \tag{2}$$

4.3. Excess air

It is supplied to ensure complete combustion by proper mixing of air and fuel. Combustion efficiency is improved by supplying air in excess. It increases the heat losses but minimizes the CO formation. It is measured from the oxygen in the flue gas leaving the stack. Atmospheric air contains 21% of O_2 by volume. It has a great effect on the performance of boiler.

$$EA = \frac{\%O2\ in\ flue\ gas}{21 - \%\ O2\ in\ flue\ gas} = \frac{4.2}{21 - 4.2} = 25\% \tag{3}$$

4.4. Actual air

Actual air is a product of theoretical air and excess air factor.

$$m_{actual\ air} = (1 + 0.25)\ 3.53 = 4.41\ \text{kg} \quad m_{flue\ gas} = 4.41 + 1 = 5.41\ kg \tag{4}$$

4.5. Dry flue gas loss

The flue gases contain dry as well as wet products of combustion. Loss due to wet products of combustion is calculated separately. Heat energy in the flue gas should be recovered by the use of suitable waste heat recovery systems.

$$Q_{flue\ gas} = \frac{5.36\ X\ 0.23\ X\ (140 - 32)}{2650} = 5\% \tag{5}$$

4.6. Loss due to moisture in the fuel

$$Q_{moisture\ in\ fuel} = \frac{0.5050\ X\ (584 + 0.45\ (140 - 32))}{2650} = 12\% \tag{6}$$

4.7. Loss due to evaporation of water

$$Q_{evaporation\ of\ H2O} = \frac{9\ X\ 0.022\ (584 + 0.45\ (140 - 32)}{2650} = 4.7\% \tag{7}$$

4.8. Loss due to moisture in the air

$$Q_{moisture\ in\ air} = \frac{4.36\ X\ 0.01\ X\ 0.45\ X\ (140 - 32)}{2650} = 0.08\% \tag{8}$$

4.9. Loss due to incomplete combustion

$$Q_{incomplete\ combustion} = \frac{0.1\ X\ 0.2750}{0.1\ + 19}\ X\ \frac{5744}{2650} = 0.31\% \tag{9}$$

4.10. Radiation and convection losses

Radiation effect is considered small compared to conventional boilers. It is mainly governed by Stefan Boltzmann law. Radiation and convection losses are assumed to be 0.5%.

4.11. Sulphation credit

This represents the heat gain because of the exothermic nature of the reaction.

$$Heat\ gain = \frac{4\ X\ 0.7\ X\ 15141\ X\ 100\%}{11092} = 3.82\% \tag{10}$$

4.12. Forced draft (FD) fan credit

FD fan minimizes some of the pressure drops in the combustor by providing the required quantity of air. This credit for 250 MW boiler is assumed to be 1%.

$$\eta = 100 - (5 + 12 + 4.7 + 0.08 + 0.31 + 0.5) + 3.82 + 1 = 82.23\% \tag{11}$$

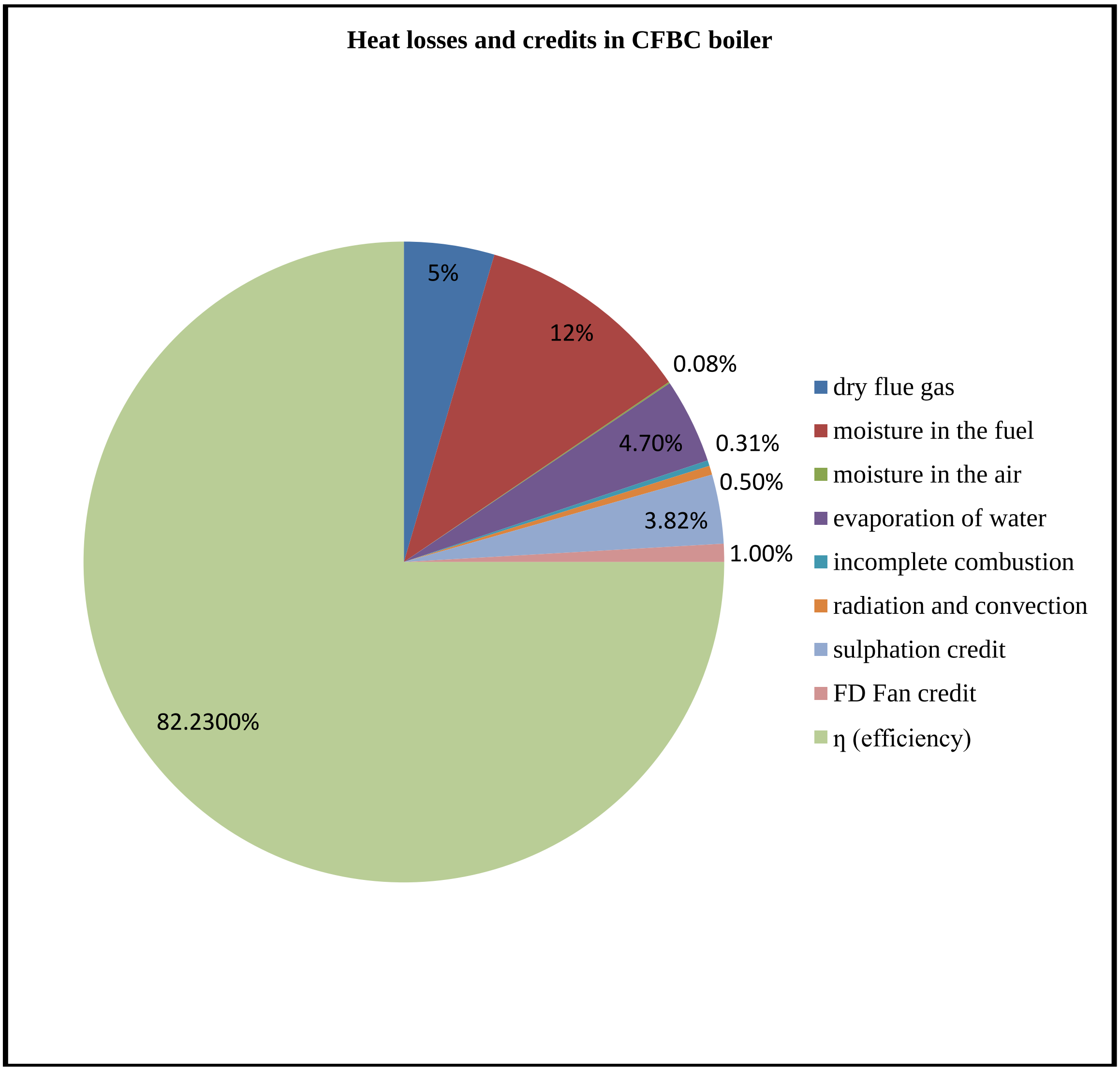


Fig.3 Heat losses and efficiency of CFBC boiler

In this special type of boiler there are heat credits apart from heat losses. Heat credits include Sulphation credit and forced draft fan credit. When the calcined limestone (CaO) reacts with Sulphur di oxide (produced from Sulphur in coal), Calcium sulphate (CaSO4) is formed according to the reaction

$$SO_2 + CaO + \frac{1}{2} O_2 \longrightarrow CaSO_4 + 15141 \text{ kJ/kg}$$

The above reaction is exothermic in nature. So there is gain of heat to the furnace which results in better heat transfer characteristics and improvement in efficiency.

5. RESULTS AND DISCUSSIONS

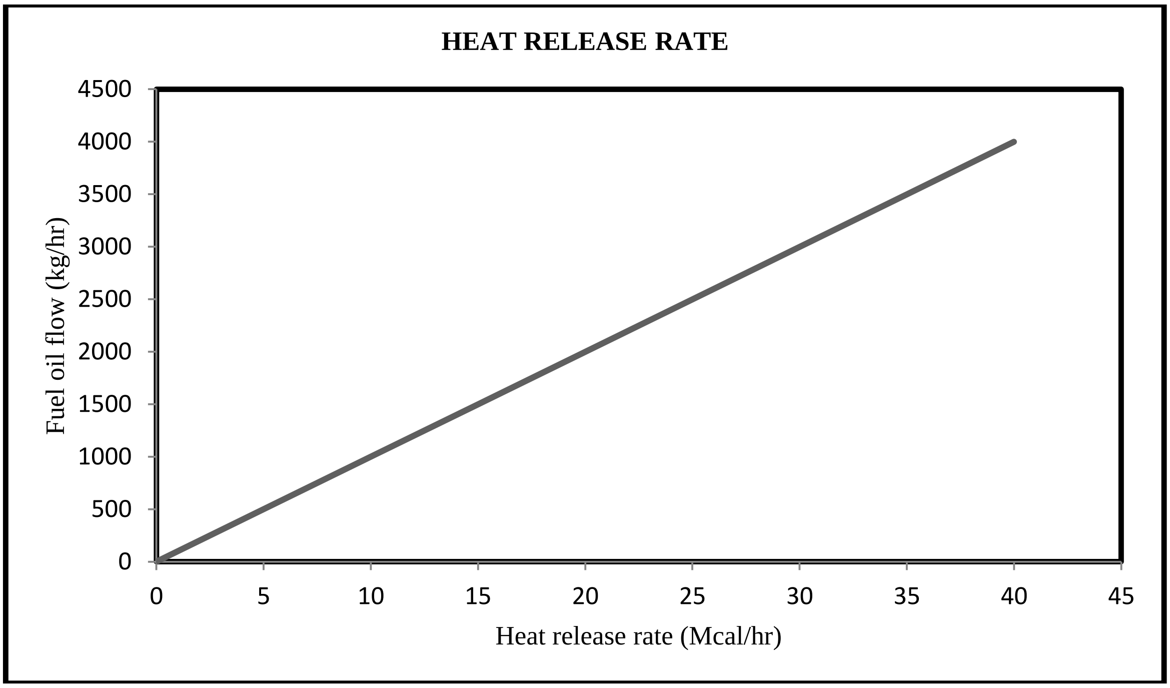


Fig. 4. Heat release rate vs. Fuel oil flow

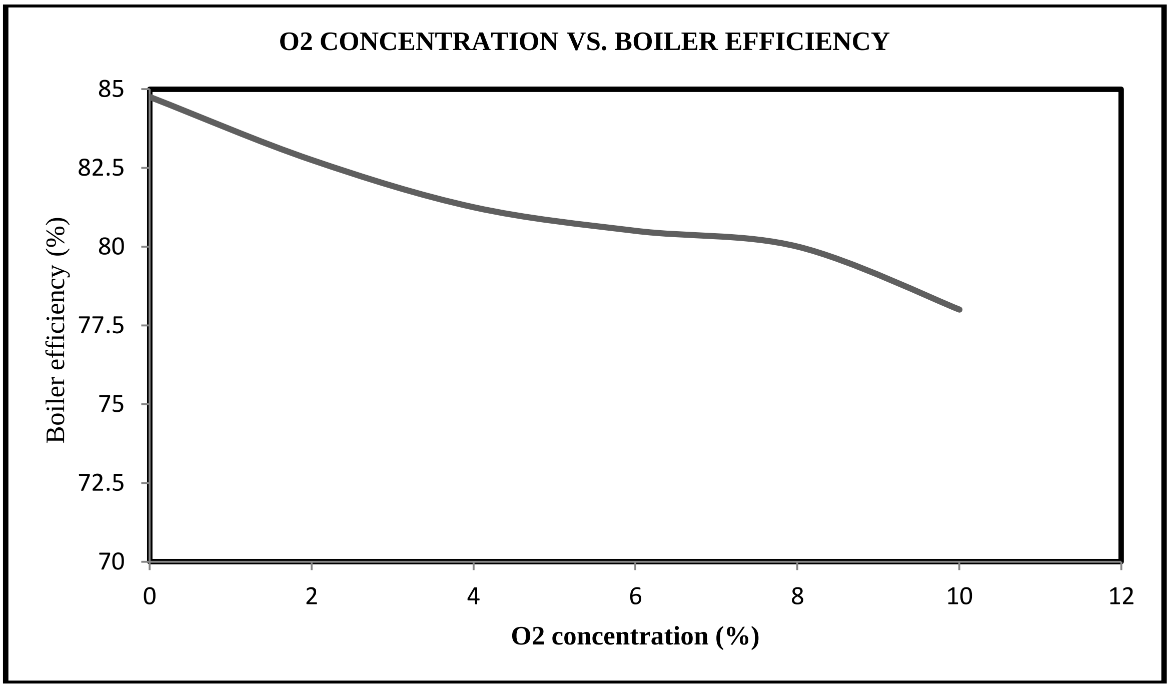


Fig 5. Oxygen concentration vs. Boiler efficiency

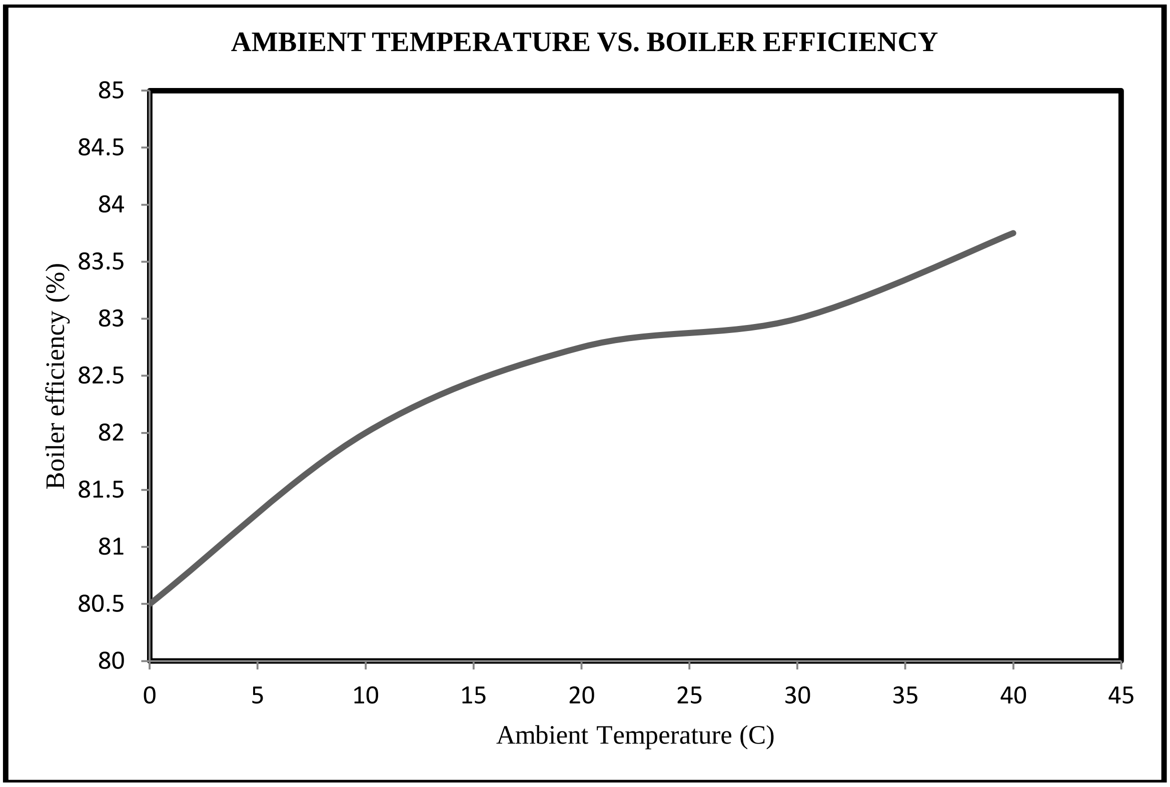


Fig. 6. Ambient Temperature vs. Boiler efficiency

5.1. Hydrodynamics of fluidized bed

Archimedes number is given by

$$Ar = \frac{\rho_g\, d_v^3\, (\rho_S - \rho_g) g}{\mu^2} \qquad d_V \approx 1.13 d_P \tag{12}$$

$$Ar = \frac{1.22\, X\, 339^3 X 10^{-18} X\, (2660 - 1.165)\, X\, 9.81}{0.000018^2} = 3827 \tag{13}$$

$$Re_{mf} = (1135.7 + (0.0408\, X\, 3827))^{0.5} - 33.7 \quad (Geldart) \tag{14}$$

$$Also\;\; Re_{mf} = \frac{\rho_g\, U_{mf} d_P}{\mu}$$

$$Re_{mf} \approx 3$$

$$\Rightarrow 3 = \frac{1.22\, X\, U_{mf}\, X\, 300\, X\, 10^{-6}}{0.000018} \qquad \Rightarrow U_{mf} = 0.25\, \frac{m}{s} \tag{15}$$

Geldart has given some algebraic relations between the Reynolds number at minimum fluidization and the Archimedes number. Reynolds number lies in the Transition region and the Archimedes number which explains the regimes of Fluidization comes to 3827. Minimum fluidization velocity has magnitude of 0.25 m/s. The algebraic relation between Reynolds number and Archimedes number can be used only for particles greater than 100 microns. Since the particle size is of order of 300 microns the relation holds good. To be more precise the equation can be used for Group B and Group D solids.

5.2. Pressure drop

Pressure drop per unit height of the bed is given by the formula

$$\frac{\Delta P}{H} = (\rho_p - \rho_g)g = 26.083\ KPa \qquad (16)$$

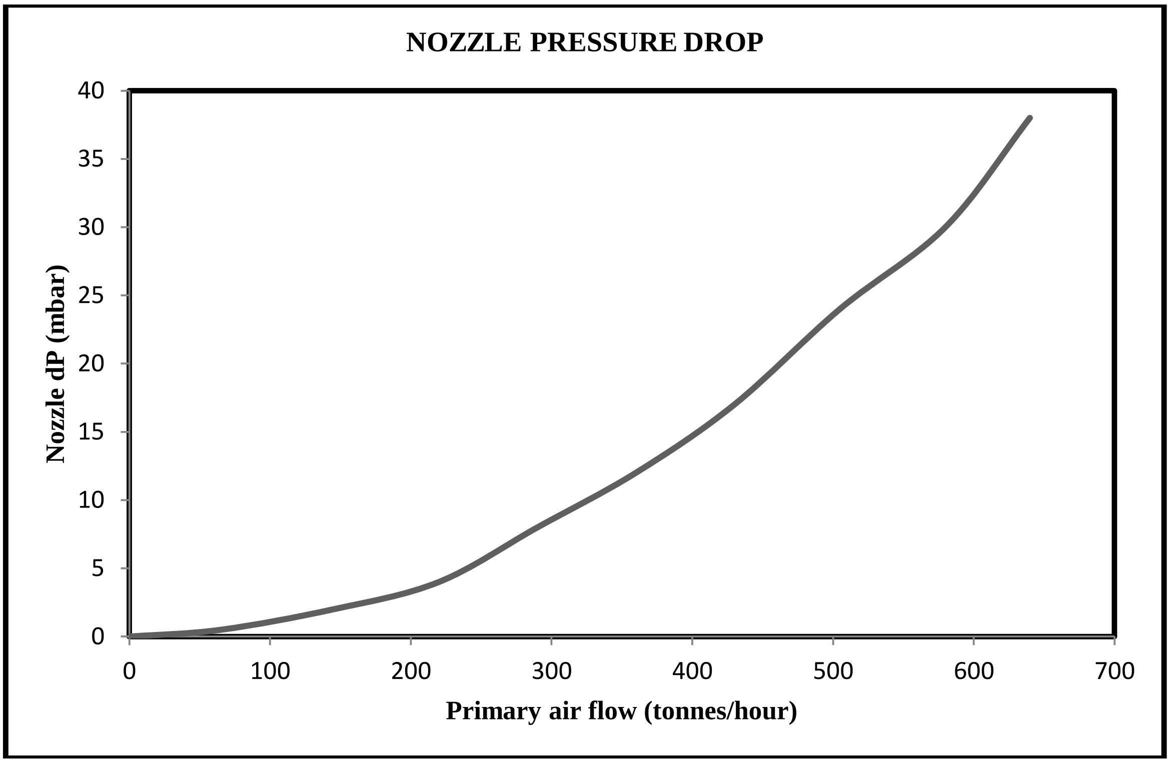


Fig.7. Primary air flow vs. Nozzle Pressure drop

It can be observed that the nozzle pressure drop increases with increase in Primary air flow rate. The minimum fluidization velocity decreases as the pressure increases. Minimum fluidization velocity is defined as the velocity at which the particles just get lifted up. With a further increase in velocity intense mixing (turbulence) occurs. As the velocity increases further the particles begin to move up the combustor and get entrained or elutriated.

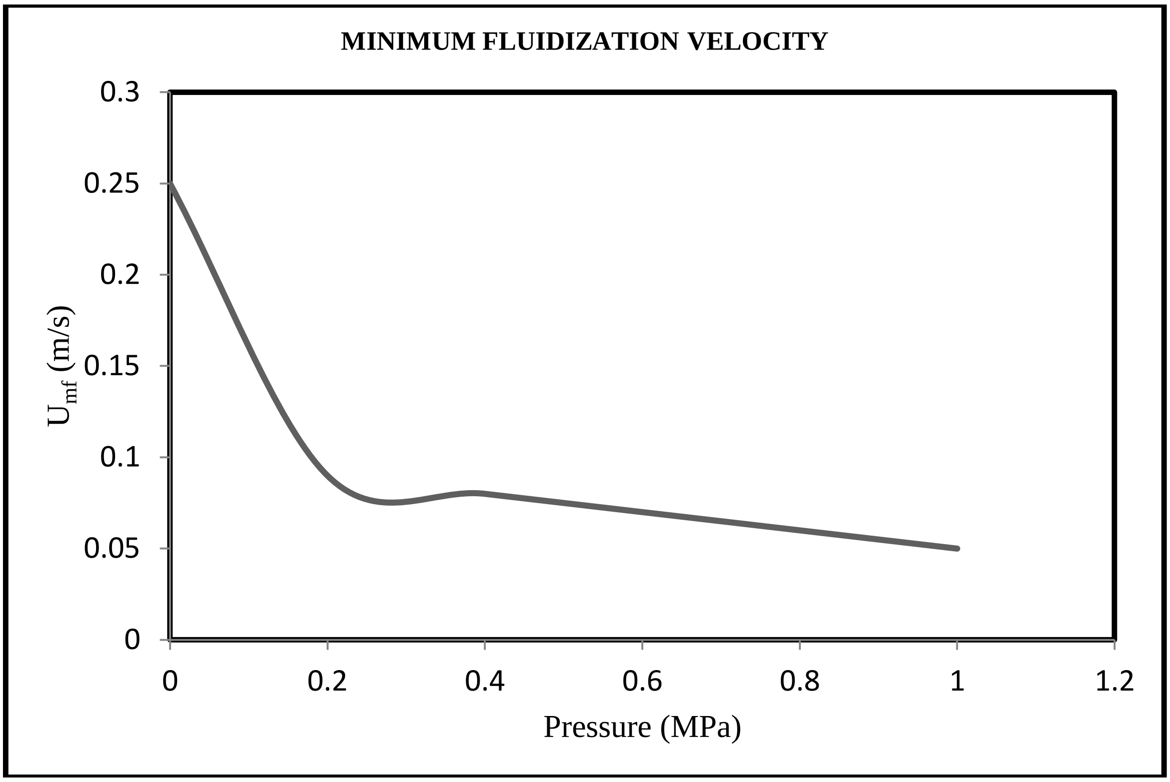


Fig.8. Minimum Fluidization velocity vs. Pressure

5.3. Heat transfer analysis

Gas solid system is a highly satisfactory thermal system when the operational behavior is well understood. The heat transfer coefficient between a surface and a gas solid suspension is a function of particle convection, gas convection and radiation.

$$h = h_P + h_g + h_r \tag{17}$$

A fluidized bed of particles is capable of exchanging heat very effectively with the fluidizing gas because of very large surface area exposed by the particles (3000 – 45000 m^2 / m^3). Highest rates of heat transfer between a bed and surface are obtained when there is rapid exchange of material directly adjacent to the transfer surface and the bulk of the bed i.e. when the particle residence time is very short. Heat transfer is maximum when the particles are finer. For a fixed bed heat transfer coefficient is minimum. h value increases with the fluidization and is maximum when the bed is fully fluidized. h value is maximum at the optimum fluidizing velocity. Afterwards there is a dip in the h value as the velocity exceeds the optimum fluidizing velocity.

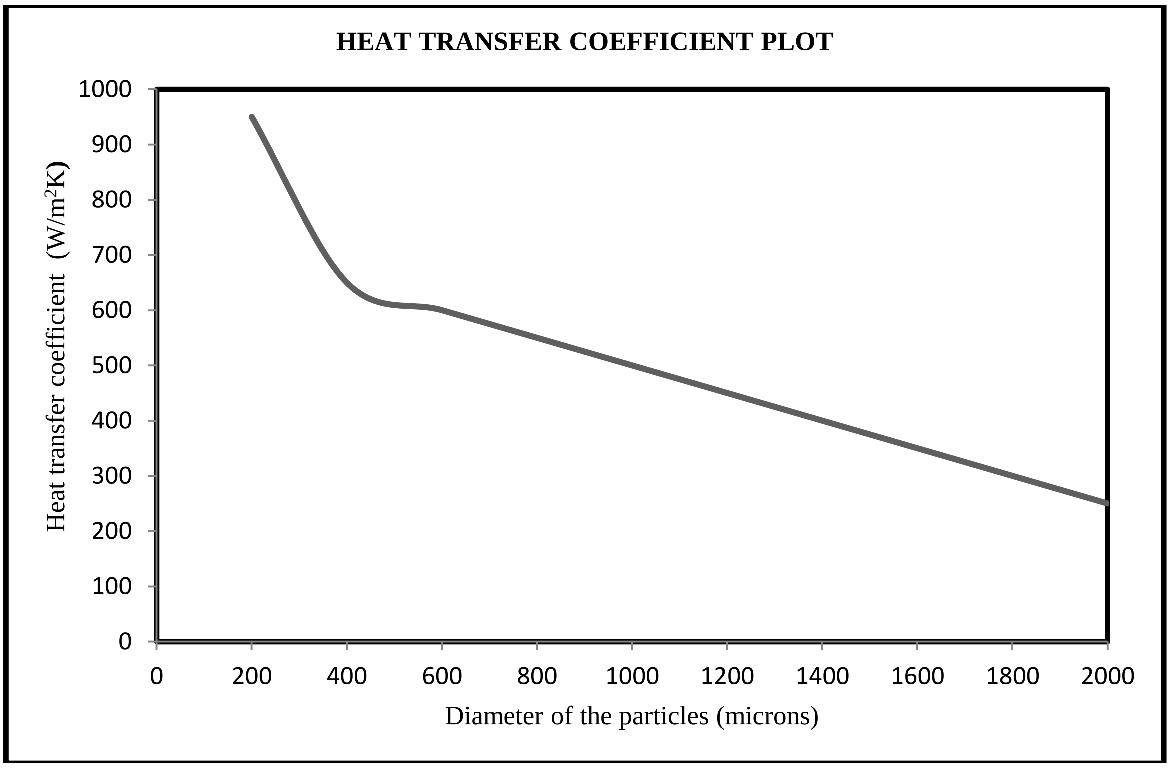


Fig.9. Heat transfer coefficient vs. diameter of the particles

5.4. Flue gas analysis

Flue gas carry enormous amount of heat which can be utilized to improve the performance of boiler. Oxides of Sulphur and nitrogen should be monitored and controlled. No Flue gas desulphurization and Flue gas denitrification plant is required for CFBC combustors as Sulphur is very well captured at the bottom of the combustor using limestone. This shows CFBC is an environment friendly technology.

Table 5. Flue gas composition

Gas	**% by volume**
N_2	62.5
CO_2	11.5
H_2O	21.9
O_2	4.2

5.5 Simulation of fluidized beds

Simulation was performed using the FLUENT software and results were obtained for expansion of the bed. A set of conservation equations are solved including one equation for each phase using the kinetic theory of granular flow or other empirical relation. The Eulerian model gives a set of equations as it solves continuity and momentum conservation equations for each phase. Pressure and momentum exchange coefficients couple the set of equations. The kinetic theory is used to introduce the properties of granular flows. With computational fluid dynamics (CFD) it is possible to get a detailed view of the flow behavior of the fluidized beds.

The FLUENT CFD code has extensive interactivity, so that we can make changes to the analysis at any time during the process. This saves time and enables to refine designs more efficiently. Graphical user interface (GUI) is intuitive, which helps to shorten the learning curve and make the modeling process faster. The numerical solution of Navier–Stokes equations in CFD codes usually implies a discretization method: it means that derivatives in partial differential equations are approximated by algebraic expressions which can be alternatively obtained by means of the finite-difference or the finite-element method. Finite volume method is implemented in FLUENT.

Contours of Volume fraction (phase-2) (Time=0.0000e+00)

Mar 07, 2013
FLUENT 6.3 (2d, pbns, eulerian, lam, unsteady)

Fig.10. Initial condition of the fluid bed $U < U_{mf}$

At the initial condition the volume fraction of the solids is taken as 0.4 when $U < U_{mf}$. The fluidizing medium just percolates the void spaces between the stationary particles. With the increase in flow rate particles move apart, vibrate and the bed expands which is shown subsequently. At higher velocities, a point is reached where all the particles are just suspended by the upward flowing gas. The bed is said to be in incipient stage. Steady circulation of solids is maintained for a stable condition of the bed and the bed is known as circulating fluidized bed. The pant leg is filled with 40%

of solids upto 12 m height level. Solids include Lignite particles and Limestone. The air distributor nozzle provides the necessary air for Fluidization.

Coarser particles are easier to fluidize but difficult to entrain. They have inertia and particle dynamics is governed by the law of gravity. The above contour is for 300 microns. These particles do not bubble in the combustor and easily get entrained. They do not exhibit instabilities in the bed. On the other hand coarser particles because of voids between them exhibit much instabilities in the bed. They are subjected to channeling etc. Finer particles exhibit better dynamic characteristics because of more amount of intermolecular force or bond between them. Mixing is better for them and hence combustion is better.

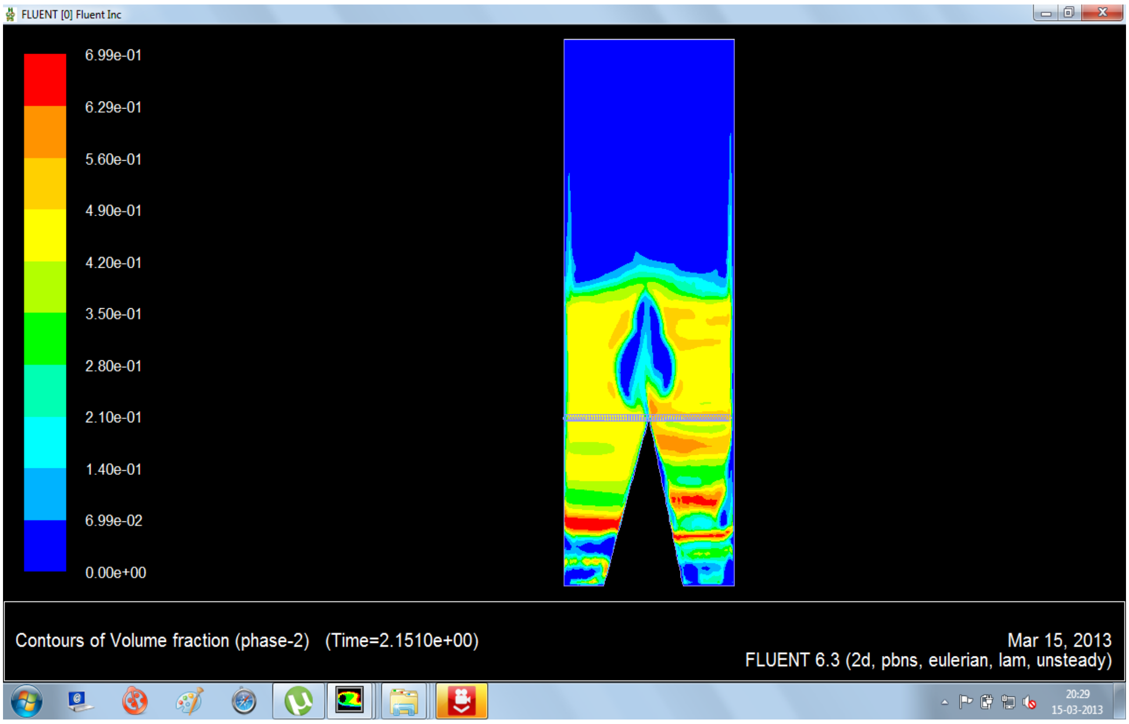
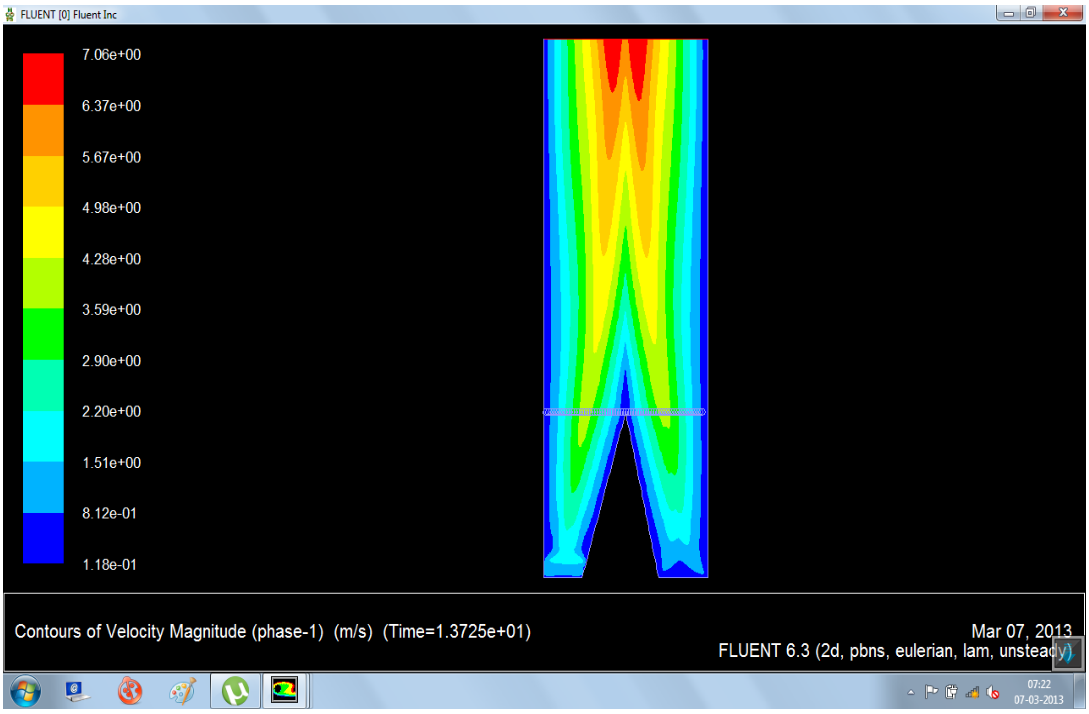


Fig.11 Condition of the fluid bed after expansion, $U > U_{mf}$

The air supplied is mainly divided into Primary air, Secondary air and Fluidizing air. Of this fluidizing air forms about 40% of the total air supplied. The velocity of the fluidizing air is in the range of 5 -7 m/s. Primary air is meant for drying of lignite particles i.e. removal of moisture. Secondary air is meant for combustion and fluidizing air is meant for suspension of solids



Contours of Velocity Magnitude (phase-1) (m/s) (Time=1.3725e+01)

Mar 07, 2013
FLUENT 6.3 (2d, pbns, eulerian, lam, unsteady)

Fig 12. Contour of velocity distribution of air (m/s)

The difference between the solids velocity and the air velocity is known as slip velocity. Slip velocity is obtained as 3 – 5 m/s. As the solid particles are fluidized by passing air or other medium they exhibit fluid like behavior. With an increase in flow rate of the fluids, particles move apart and a few vibrate. This is called the expanded bed. At higher velocities a point is reached where all the particles are suspended by the upward flowing gas or liquid. The frictional force between the particle and the fluid just counterbalances the weight of the particle. The Particles are in a suspended state. With a further increase in air velocity the particles gets lifted up as the buoyancy force becomes dominant than the gravitational pull. The bed is said to be in a fluidized state. With further increase in air velocity the particle gets entrained from the combustor. It then enters the cyclone, then reaches the seal pot via the down comer and then is returned back to the combustor.

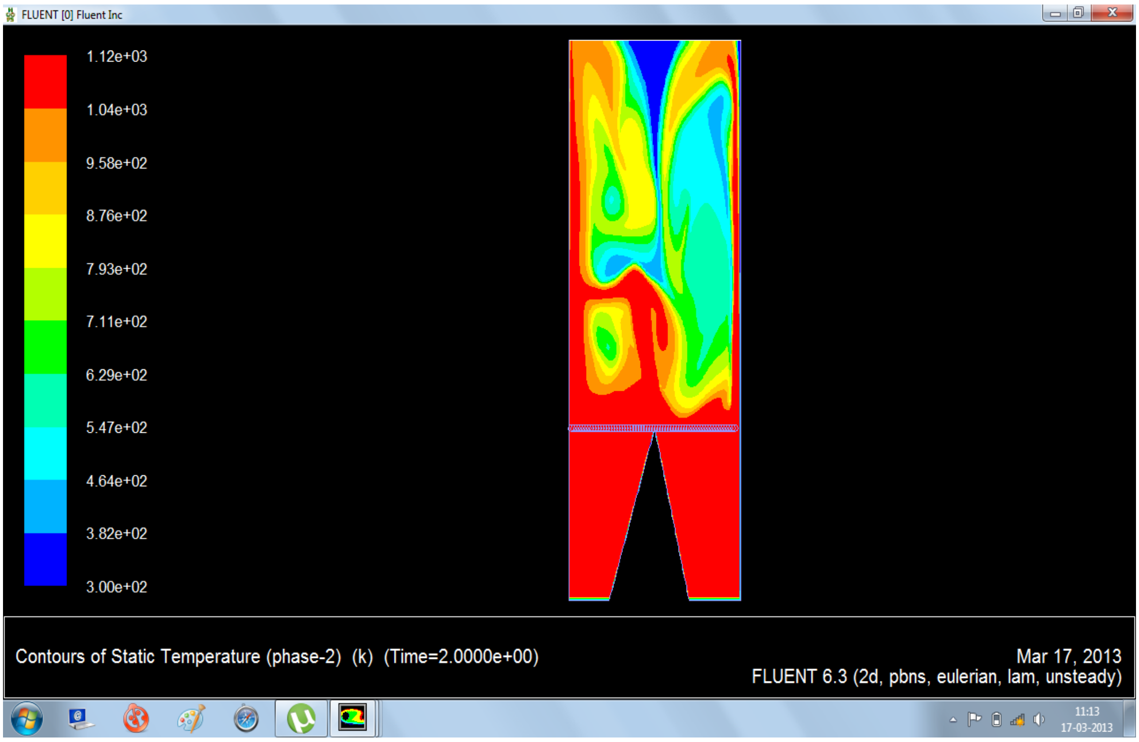


Fig.13 Contour of Temperature distribution of solids (K)

One of the main advantage of the fluidized bed is that is the uniformity of temperature (800 – 950 degree C) which leads to uniform thermal strain throughout the combustor. Fluidized bed is metallurgically stable. Erosion of walls of the combustor due to ash clinkering is not a major issue since the temperature is well below the ash fusion temperature. The life of the combustor is more as it is subjected to uniform thermal stress.

The Temperature at bottom portion of the combustor and top portion of the combustor vary. This is due to firing takes place from the bottom of the combustor. Bottom portion of the combustor is at a temperature of 850 – 900 C while top portion of the combustor is at a temperature of 800 – 850 C. But the thermal conditions in the bed are more or less uniform in nature.

5.6. Discussions and inferences

Coarser particles are easier to fluidize but difficult to entrain. They have inertia and particle dynamics is governed by the law of gravity. These particles bubble in the combustor and very few particles get entrained. They exhibit large amount of instabilities in the bed. Finer particles are easier to entrain but difficult to fluidize, the reason behind being the intermolecular force between the molecules. They are densely packed. Hence in order to fluidize the particles large amount of air has to be supplied with the help of blowers and fans. Hence auxiliary power consumption is slightly more in the case of fluidized bed boilers. This can be minimized if the particles are properly sized i.e. the particles should neither be too coarser nor too finer. Particle size has a great role to play in the hydrodynamics of the gas solid system.

CONCLUSION

From the energy loss method of boiler performance assessment it is concluded that efficiency of the boiler based on GCV is 82.23%. The reduction in the overall efficiency is mainly due to the presence of excess moisture (50.50%) in the fuel. The efficiency can still be increased by use of high quality coal with less moisture content and with higher calorific value. The efficiency can increased upto 85 - 90% by employing supercritical technologies which will have to be investigated in the future. The bed pressure drop is a strong function of solids inventory in the system.

Heat transfer characteristics are better for finer particles. But from hydrodynamics point finer particles are difficult to fluidize as the molecules are closely packed. Hence a little compromise should be made in selecting the particle size in such a way that it is not too finer nor too coarser. When this condition is met heat and mass transfer is maximum and results in better efficiency due to favorable hydrodynamic condition and better heat and mass transfer characteristics. The heat transfer coefficient is maximum at the bottom of the bed where the bulk density of solids is maximum.

CFD simulation of the hydrodynamics of the 2 phase fluidized bed has been carried out by employing the Eulerian approach. Hydrodynamic variables like velocity distribution, volume fraction of the solids (VOF), pressure drop, bed expansion and bed voidage were studied. The magnitude of velocity was found to be more away from the wall. The smaller particles gain more velocity than the larger particles in the fluidized bed. Heat transfer coefficient agrees with the experimental value with a reasonably good accuracy

NOMENCLATURE

Ar	Archimedes number
C_D	Particle drag coefficient
C_P	Specific heat [kJ / kg K]
d_P	Diameter of the particle [m]
F_B	Buoyancy force [N]
F_D	Drag force [N]
F_G	Gravity force [N]
g	Acceleration due to gravity [9.81 m / s^2]
h	Heat transfer coefficient [W / m^2 K]
h_g	Gas heat transfer coefficient [W / m^2 K]

h_p	Particle heat transfer coefficient [W / m^2 K]
h_r	Radiative heat transfer coefficient [W / m^2 K]
h_w	Wall heat transfer coefficient [W / m^2 K]
H_b	Bed height [m]
HF	Humidity factor
k	Thermal conductivity of the gas [W / mK]
$m_{actual\ air}$	Mass of the actual air [kg]
m_b	Mass of the bed (fixed or fluidized) [kg]
m_{flue}	Mass of the flue gas [kg]
m_p	Mass of the particle [kg]
$m_{theoritical\ air}$	Mass of the theoretical air [kg]
M	Moisture content
ΔP	Pressure drop [kPa]
$Q_{bottom\ ash}$	Heat loss due to bottom ash [kJ]
$Q_{fly\ ash}$	Heat loss due to fly ash [kJ]
$Q_{incomplete\ combustion}$	Heat loss due to incomplete combustion [kJ]
$Q_{moisture\ in\ air}$	Heat loss due to moisture in the air [kJ]
$Q_{moisture\ in\ fuel}$	Heat loss due to moisture in the fuel [kJ]
$Q_{evaporation\ of\ H2O}$	Heat loss due to evaporation of water [kJ]
$Q_{flue\ gas}$	Heat loss due to flue gas [kJ]
Re	Reynolds number
Re_{mf}	Reynolds number at the minimum fluidization
$T_{ambient}$	Ambient temperature [K]
T_{flue}	Temperature of the flue gas [k]
u_P	Velocity of the particle [m / s]
U_{mf}	Minimum fluidization velocity [m / s]
U_{opt}	Optimum velocity of fluidization [m / s]
V_P	Volume of the particle [m^3]

LIST OF SYMBOLS

Φ_P	Sphericity of the particles
ρ_b	Bulk density of solids [kg / m^3]
ρ_f	Density of the fluid [kg / m^3]
ρ_p	Particle density [kg / m^3]
ε	Voidage of the particles
ε_{mf}	Voidage of the particles at the minimum fluidization
μ_f	Dynamic viscosity of the fluid [Ns / m^2]
η	Efficiency of the boiler [%]

LIST OF ABBREVIATIONS

AAS	Actual air supplied
CFBC	Circulating fluidized bed combustion
CFD	Computational fluid dynamics
GCV	Gross calorific value
EA	Excess air
FBHE	Fluidized bed heat exchanger
VOF	Volume fraction

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