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Combustion Characterization of a Pulverized Coal 210 MW Boiler through Computational Fluid Dynamics Approach

V. Saravanan*, Ramakrishna* and S. Seetharamu*

This study consists of the numerical simulation (based on commercial CFD code) of the flow and combustion processes that take place in the furnace of a 210 MW pulverized coal utility boiler. The modeling has been done for various conditions like coal mass flow and particle size distribution from different burner levels. The modeling has also been carried out for different burner tilt angles. The effects of these conditions in terms of unburnts, heat flux distribution, emissions, actual heat energy utilized in the boiler, heat loss in terms of unburnts and heat carried away by flue gas have been brought out in this paper.

1.0 INTRODUCTION

There has been a dramatic increase in recent years in the use of comprehensive Computational Fluid Dynamics (CFD) based computational tools to model the processes in thermal power sectors owing to the pressure for cleaner and reliable power generation; tighter pollution emission regulations; reducing the time to effect modernization of old power plants; and reducing the time to bring new processes/plants for increased distributed power generation. The thermal power generation in India accounts for more than 70% of the total power generation and coal is used as a predominant fuel. Indian power station coals are sub bituminous variety, also features relatively high proportion of intergrown mineral matter besides inter-banded stone layers[1].

In any coal-fired power plants, the important phenomenon that governs the boiler performance is the coal combustion pattern within the furnace. In India, most commonly available are the pulverized coal (PC) fired power plants. The PC combustion is a complex process[2] and the combustion of coal particles follows a sequence of processes, which are partly overlapping and are dependent on both physical conditions and coal properties[3]. The coal combustion involves heavy turbulence and complicated heat transfer mechanisms and this includes heat flux distribution, thermodynamics of particle and gas flow and combustion kinetics involving devolatilisation and char oxidation. The quantity of coal and air can be monitored and controlled before introducing into the boiler but practically it is very difficult to monitor the pattern of combustion process within the furnace, which is the deciding factor for many problems in the boiler. CFD modeling is an advanced tool, which can open up the black box and take a peek at what is happening inside the furnace chamber.

This paper deals with the CFD modeling carried out for a 210 MW pulverized coal corner fired power plant. The commercial CFD code CFX-4 has been used for this purpose. The effects of coal mass flow and particle size distribution on the power plant performance in respect of coal combustion kinetics, unburnt levels, heat flux distribution, heat energy utilized by the boiler, etc. have been discussed in this paper. The effect of various burner tilt operations on the temperature profile of the boiler has also been brought out.

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*Central Power Research Institute, Sadashivanagar, Bangalore 560 080, India

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2.0 CASE STUDY BOILER DESCRIPTION

In this study, the furnace of an existing conventional pulverized coal boiler has been simulated[4]. The selected boiler is a 210 MW Unit, corner fired by 24 burners (six elevations with four burners at each elevation among which only five elevations are used at a time ie. 20 burners). The basic fuel is a sub-bituminous coal. The characteristics of the coal and the flow data of the selected boiler are given in Table. 1 & 2 respectively. Fig. 1 shows the boiler geometry.

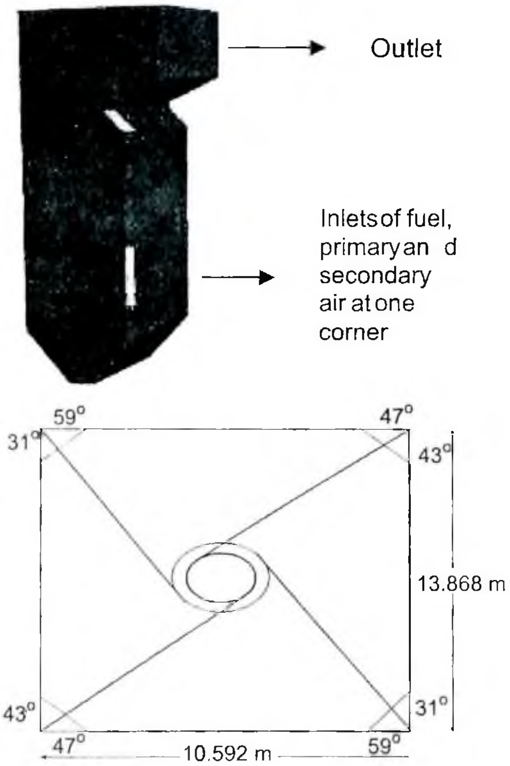


FIG. 1. BOILER GEOMETRY

TABLE 1

COAL CHARACTERISTICS

Coal characteristics	Percentage composition (%)
Moisture	7.20
Volatiles	27.6
Fixed Carbon	24.8
Ash	40.4
Carbon	41.9
Hydrogen	2.78
Nitrogen	0.94
Sulphur	0.26
Oxygen	6.52

TABLE 2

FLOW DATA

Flow Data	
Pulverized coal mass flow	130 t/h
Primary air mass flow	300 t/h
Primary air temperature	80°C
Secondary air mass flow	400 t/h
Secondary air temperature	280°C
Water wall temperature	350°C
Particle size distribution	Six different sizes
Primary air angular velocity	Varies for the burner tilts

2.1 Strategies Adopted in the Numerical Modeling

The numerical modeling was carried out using the commercial CFD code CFX-4. The work presented here implies the simulation of the following processes taking place in the furnace: turbulent flow field, coal combustion, particle transport and radiative heat transfer. The gaseous phase was modeled assuming a Eulerian approach, where as for the solid phase (coal particles), the Lagrangian approach was considered.

This approach is used to track the particle trajectories and it is based on the assumption of a dilute solution of particles in gaseous phase[5].

The gas flow was modeled by solving the Navier-Stokes equations (N-S-E) along the computational domain. The standard k-e turbulance model proposed by Launder and Spalding (1974) has been chosen because it is the most widely used model for engineering applications and it has been validated for a large amount of industrial turbulent flows.

Since the simulated phenomenon was non-isothermal, an energy conservation equation was included in the set of governing equations. This equation can be solved in terms of temperature adding the appropriate state equation (density expressed as a function of temperature and pressure) and the constitutive relationship between enthalpy, temperature and pressure.

The coal combustion is considered as a two global step process. The first step is considered as homogeneous, in which the volatile gases escape in the gaseous phase, leading to the generation of the volatile combustion products. The second step is considered as heterogeneous, because the combustion of the solid phase (char) occurs, giving off gaseous products. Due to the fact that two combustion steps are considered, the results expressed in terms of four mass fractions for fuel, oxidant, volatile combustion products and char combustion products. The volatile combustion modeling requires a previous estimation of the amount of volatile transferred to the gaseous phase. The single step devolatilisation model proposed by Badzioch and Hawksley (1970) has been selected for this purpose. This model states that the rate of production of volatile gases is given by a first order reaction and the rate constant is expressed in an Arrhenius form.

Regarding the volatile gas combustion, the Mixed-is-Burnt (MIB) model was used under the assumption of infinitely fast chemistry. This model, originally proposed by H.Rummel and fully developed by Warnatz et al. (1996) assumes that fuel and oxidant cannot co-exist instantaneously. The instantaneous mass fractions are given in terms of the instantaneous mixture fraction. The mean mass fractions of fuel, oxidant and products are obtained from the mean and variance of the mixture fraction, using an assumed form for the probability density function (PDF) of the mixture fraction. Here, a double delta function was assumed.

The char oxidation is a much slower process than devolatilisation, and it therefore determines the burnout time of pulverized coal in the furnace. In this case, the selected model was the one proposed by Field et al (1967). In this approach, the char oxidation is modeled as a global reaction of order unity and the reaction rate is calculated on the assumption that the process is limited by the diffusion of oxygen to the external surface of the char particle and the char reactivity.

When modeling the coal combustion, it is necessary to combine the combustion models with a particle transport modeling, the total mass flow of coal particles has been modeled by tracking a number of trajectories much lower than the real number of particles, assuming that each simulated particle represents a sample of the real number of particles. In this simulation, a total number of 3000 trajectories have been tracked.

The radiative heat transfer was simulated according to the Discrete Transfer method proposed by Lockwood and Shah (1981). The discrete transfer model was built on the concept of solving the radiation transfer equation for representative rays in the combustor. The integration of the radiation transfer equation along the path provides an equation for the intensity changes caused by all rays passing through a cell. In the present simulation a total number of 12 rays was used.

2.2 Boundary Conditions

2.2.1 Inlets

Angular velocities (calculated for primary, auxiliary and secondary air), turbulence intensity (commonly between 0.03 and 0.08), dissipation length scale (it is geometry dependent; a suitable choice is set equal to the hydraulic diameter of the inlet), flow temperature, emissivity and roughness were set at the burner inlet.

2.2.2 Wall boundaries

Temperature, emissivity and roughness were specified for the walls.

2.2.3 Outflow boundaries

A pressure patch was specified at the outlet and a relative negative pressure of $-80\,\mathrm{N/m^2}$ was specified along with emissivity and roughness.

Five particle sizes (0 to 300μm) were simulated and the option "Uniform Distribution" was adopted for simplifying the model. The algebraic multi grid solver (AMG) was used for solving the equations.

3.0 RESULTS AND DISCUSSIONS OF THE SIMULATIONS

In thermal power plants the efficiency is measured in terms of heat rate i.e. Heat Input/ Power output (kcal/kWhr). The source energy for the entire process is the chemical energy available from the coal and in the boiler, the coal is burnt and the chemical energy is converted into heat energy and this is used for steam generation.

The boiler efficiency is depending on many factors like the coal quality, combustion reactivity, level of unburnts, heat transferred to the water walls, heat carried away by the flue gas, heat absorbed by the ash deposits, heat of vaporization of moisture, etc. The boiler operating conditions like burner tilts, excess air, burner configuration, etc also affect the boiler efficiency significantly. A delicate balance to be made to adjust the boiler operating conditions with respect to the quality of coal used to get better boiler efficiency. The complex physico-chemical reactions involved in the combustion process are governed by the coal quality in terms of macerals and minerals and also the boiler operating conditions.

In this simulation, the combustion process is studied for a sub-bituminous Indian coal in a 210 MW utility boiler for various plant operating conditions. The effect of particle size on the devolatilisation and char oxidation mechanisms, the level of unburnts expected with respect to the particle size, the effect of burner tilts on temperature profile and the effect of uneven distribution of mass flow from the burners are studied.

3.1 Effect of Particle Size on Devolatilisation and Char oxidation Processes

In the power plants the particle fineness is decided by the pulverizer performance. The particle size distribution is parabolic and the pulverizer is generally sized for a 'design' coal that typically requires the fineness of pulverized coal should be such that 70% passes through a 75 microns screen (200 mesh)[6]. However, its is generally observed that more than 30% of the coal will be coarser than 75 microns and the laboratory analysis of coals indicate that the occurrence of particles of sizes 150-300 microns are quite common[7].

The combustion reactions are significantly influenced by particle fineness. The distribution of coarser particle size reduces the combustion efficiency. In this study, the combustion modeling has been carried out for the coal particles of size 61,105,148,235 and 278 microns[8].

Fig. 2 represents the devolatilisation pattern of the selected particle sizes. The time-devolatilisation history (Fig. 2) gives the full information about the ignition time, time taken for the smallest particle size (61 microns) and largest particle size (278 microns) to complete devolatilisation. Fig. 3 and Fig. 4 represent the char oxidation and amount of unburnt carried away by the ash particles with respect to various particle sizes.

The char oxidation process is the slowest process in the coal combustion sequence and is the rate-determining step in the combustion kinetics. This is very clearly observed from the figures 2 and 3, the average devolatilisation process completes within 60 ms and char oxidation for lowest particle size (61 microns) itself takes 8s to complete. The higher size particles (148-278microns) have not completed their char oxidation even after long residence time and leave the furnace with unburnts. Fig. 4 shows the level of unburnts carried away by the particles of various sizes.

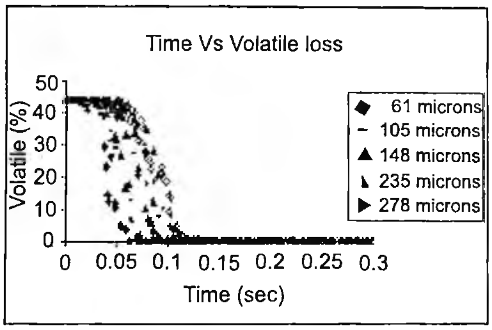


FIG. 2. DEVOLATILISATION PATTERN

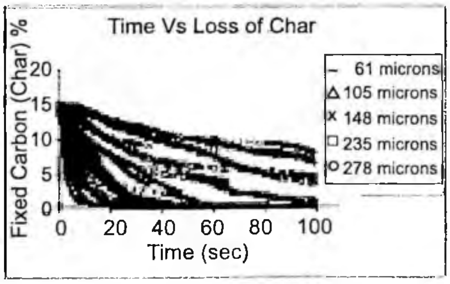


FIG. 3. CHAR OXIDATION PATTERN

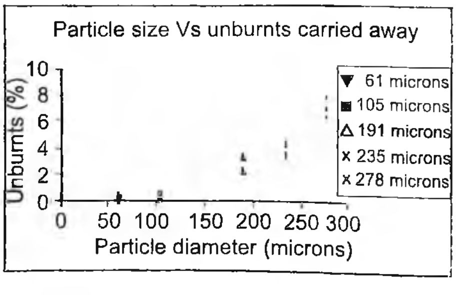


FIG. 4. UNBURNTS CARRIED AWAY BY PARTCILES

3.2 Effect of Uneven Mass Flow on Heat Flux Distribution in Tangentially Fired PC Boilers

The uneven heat flux distribution is the result of uneven coal mass distribution within the different burners of the same elevation. The 210 MW Indian boilers are generally having six mills and each mill supply pulverized coal to four different burners at one elevation. In majority of the mills, splitter vanes or mechanical separators are used to distribute pulverized coal to the individual burners. Although these devices are intended to ensure an equal mass flow of coal to each burner, in practice, flow through each coal pipeline generally varies 20% or more depending on the life and maintenance of the mill. This unbalanced distribution of coal adversely affects the air-to-fuel ratio and leads to decrease in combustion efficiency, boiler tube failures and effect on the self-regulating mechanism of steam flow in the boiler. The uneven mass flow is assessed by isokinetic sampling at all the coal flow ducts.

The effect of uneven heat flux distribution is well predicted and visualized by computational fluid dynamics modeling.

In this study uniform and uneven coal mass flow conditions have been assumed to find out the quantitative shift in fireball vortex. The figures 5 and 6 represent the mass flow distribution. The Fig. 5 represents the uniform mass flow distribution in all the burners and Fig. 6 represents 70% distribution of mass flow in the left wall and 30% mass flow in the right wall. The shifting of the vortex due to uneven mass flow towards right wall is clearly observed.

This results in the uneven distribution of heat flux towards right wall as given in Fig. 8. The difference of heat flux distribution between left and right wall is 10 times more in the case of uneven mass distribution in comparison with the case where uniform mass flow is assumed.

FIG. 5. UNIFORM MASS DISTRIBUTION

FIG. 6. UNEVEN MASS DISTRIBUTION

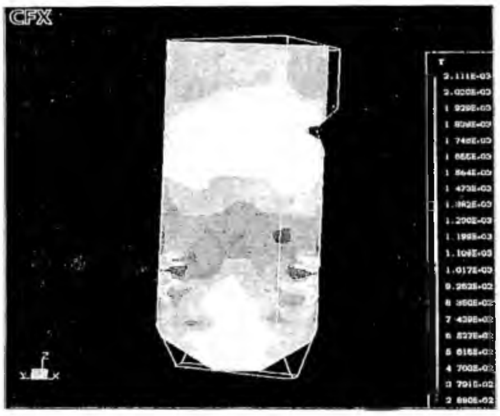


FIG. 7. UNIFORM HEAT FLUX DISTRIBUTION

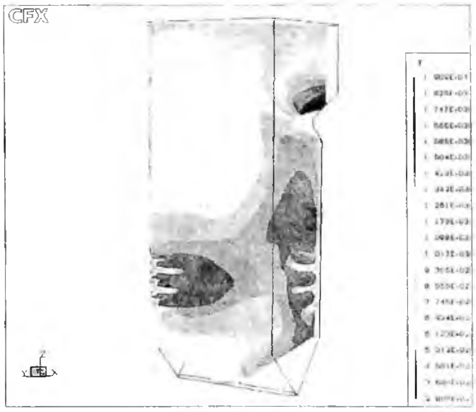
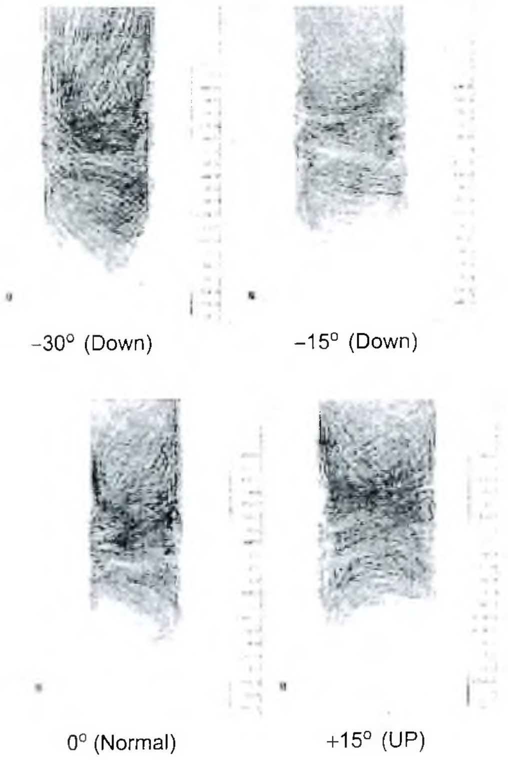


FIG. 8. UNEVEN HEAT FLUX DISTRIBUTION

3.3 EFFECT OF BURNER TILTS ON HEAT FLUX DISTRIBUTION AND FURNACE EXIT GAS TEMPERATURE

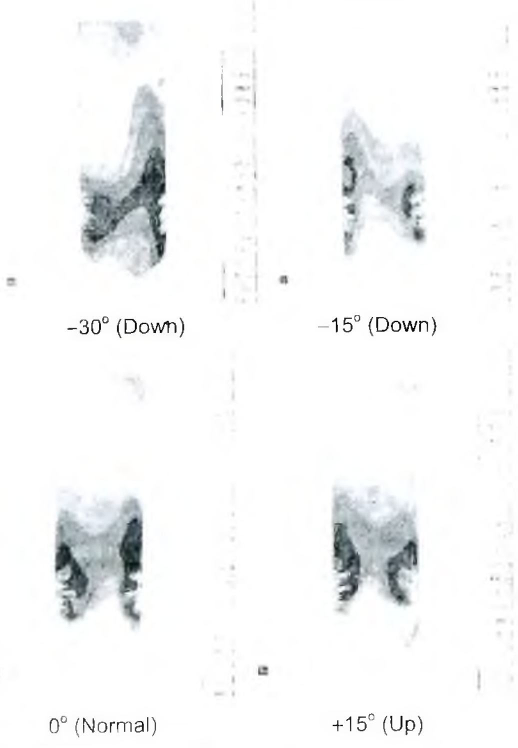
In the present modeling, the effect of different burner tilts (firing configuration) on the shift in the temperature profile and the variation in furnace exit gas temperature are studied[9].



-30° (Down) -15° (Down)

0° (Normal) +15° (UP)

FIG. 9. TEMPERATURE PROFILE FOR THE DIFFERENT BURNER TILT ANGLE CONFIGURATION



-30° (Down) -15° (Down)

0° (Normal) +15° (Up)

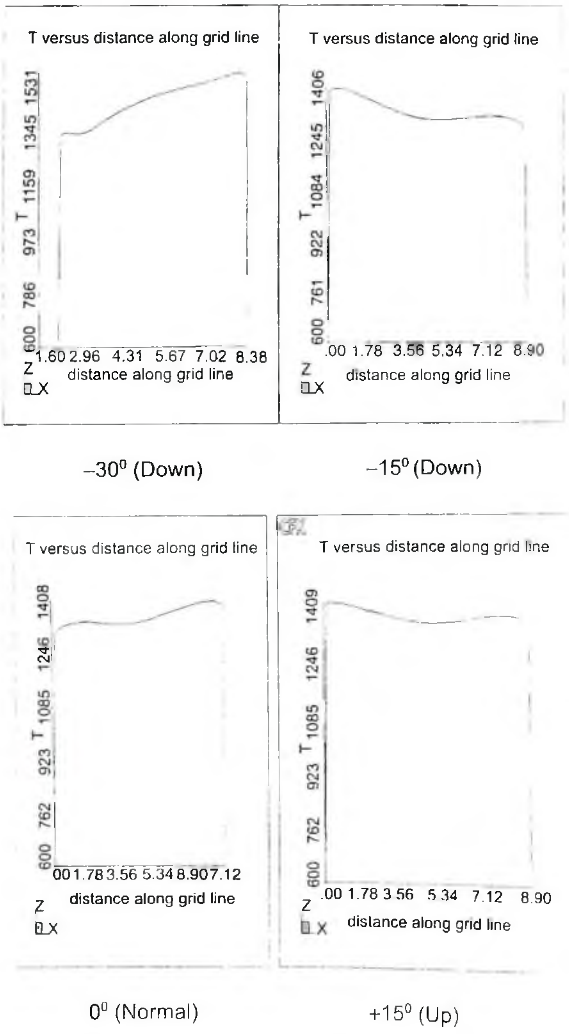
FIG. 10. TEMPERATURE (K) PROFILE AT THE CENTER VERTICAL PLANE OF THE FURNACE

3.3.1 Temperature profile of the furnace

The fireball is shifting upwards by changing the burner tilt angles −30° to +15°. The figure 10 shows the shift in the temperature profile with respect to burner tilt angles.

The Furnace Exit Gas Temperature (FEGT) is obtained by observing the temperature on an imaginary line cutting across the nose tip and the front wall of the furnace at the center vertical plane (Fig. 11). The temperature varies form 1075°C to 1165°C with respect to the burner tilt angles −30° to +15°.

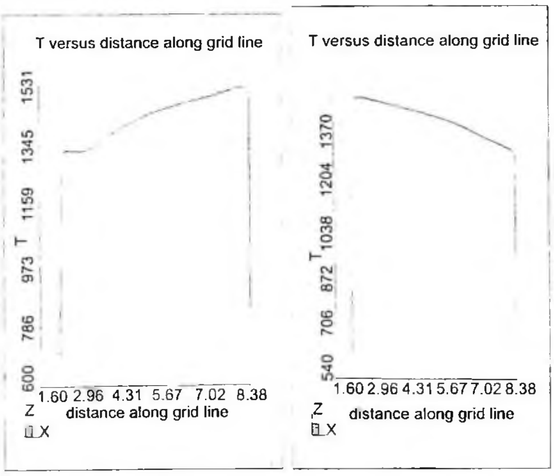
The temperature profile of the bottom ash hopper is also observed on the line across the bottom ash hopper on the center vertical plane (Fig. 12). The temperature varies from 1127°C to 927°C with respect to the burner tilt angles −30° to +15°.



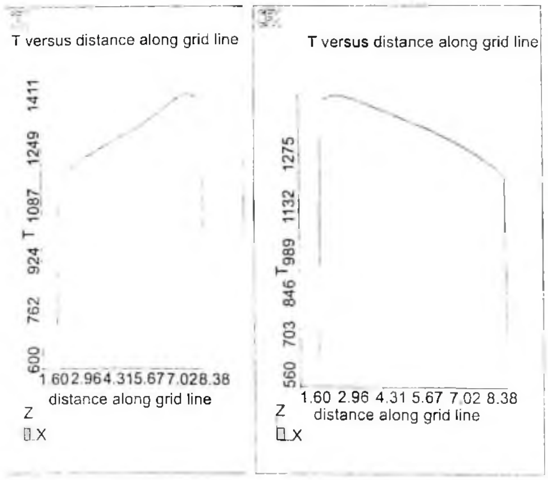
-30° (Down) -15° (Down)

0° (Normal) +15° (Up)

FIG. 11. TEMPERATURE PROFILE (K) ON THE LINE ACROSS THE FRONT WALL AND NOSE TIP ON CENTER VERTICAL PLANE



-30^0 (Down) -15^0 (Down)



0^0 (Normal) $+15^0$ (Up)

FIG. 12. TEMPERATURE PROFILE (K) ON THE LINE ACROSS THE BOTTOM ASH HOPPER ON CENTER VERTICAL PLANE

4.0 CONCLUSIONS

- Coal combustion processes must be optimized in order to minimize pollutant formation and maximize efficiency. CFD concept finds application in the combustion characterization of utility boilers
- The particle size has significant effect on devolatilisation and char oxidation mechanisms, which lead to increase in unburnt levels.
- There is a considerable shift in fireball and temperature profile when burner tilt angle is changed.
- CFD models are very useful in giving cost effective solutions for many complex systems of interest to the thermal power plants in respect of plant performance and emissions.

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