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CFD Analysis of a 210 MW Tangential Fired Boiler

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Abstract: Power generation is very important for development of Human race. Losses and efficiency takes a major role in effective utilization of energy. CFD analysis is done on the 210 MW tangentially fired pulverized tower type boiler. Temperature and velocities at different positions are obtained. Oxygen and Carbon dioxide mass fractions are estimated. Combustion behavior and coal particle trajectories are estimated. This analysis is utilized to examine the water wall and inside water flow behavior.

Keywords: Tangential fired boiler, Water wall, Temperature distribution, Velocity distribution, Heat transfer coefficient, water vapour volume fraction.

I. INTRODUCTION

The performance optimization of boiler is very important to get higher efficiencies. Optimisation should be done to increase the efficiency and life time of the boiler. The effective use of coal is crucial to conserve the fast depleting resources. It is very difficult to construct the real time boiler to test the conditions. So, it is wise and truly economical to use a computational tool (CFD) to test the boiler under different conditions [1-5]. Over the past three decades CFD has been offering promising results in the combustion modeling and boiler analysis.

To achieve higher combustion efficiency, the major influencing factors such as the particle size distribution, gas and particle temperatures, local heat release, local oxygen concentration, kinetic parameters for coal de-volatilization and char oxidation, char properties should be understood thoroughly [6-7]. The heat transfer characteristics and void fraction are very important to maintain the boiler feed water system and circulation ratio. The water volume fraction and velocities should be closely observed in order to achieve maximum heat transfer and better circulation.

Only few studies have addressed the effect of operating conditions (such as burner load, excess air etc.) in the India. In the present study, an attempt is done to estimate the temperatures, velocities and path of particles. The boiler geometry and operating conditions along with the mathematical model used are discussed in the subsequent sections. Results simulated are based on real time data.

II. Furnace geometry and operating conditions

The three-dimensional geometry was created using Catia. An isotropic view of the geometry and grid system is shown in Fig. 1. The mesh contained 172,640 nodes with 169,867 hexagonal cells. In order to make accurate quantitative predictions about combustion behavior, it is important that an appropriate geometry is created with suitable meshing techniques.

Primary, secondary and end air nozzle inlet details are taken according to the actual burner dimensions. The swirl angle is not considered for the present study. The furnace geometry of the simulated boiler can be seen in Fig. 1.

The tangential wall fired coal furnace is 61125 mm high, 12395.2 mm wide and 11557 mm deep and with an installed capacity of 210 MW. The specifications of the furnace geometry and original drawing are given in Table 1. The coal analysis is shown in Table 2.

The water walls are designed using Ansys. An istropic view of the geometry and grid system is shown in Fig 2. The mesh contains 41283 nodes with 40342 tetrahedral cells. The water wall height is of 50 m, diameter of 127 * 12.5 mm- 80 no.s and the material is SA160 – Gr.C.

Table 1 specifications of furnace geometry

Parameter (m)	Value(mm)
Height	61125
Horizontal	12395.2
Vertical	11557

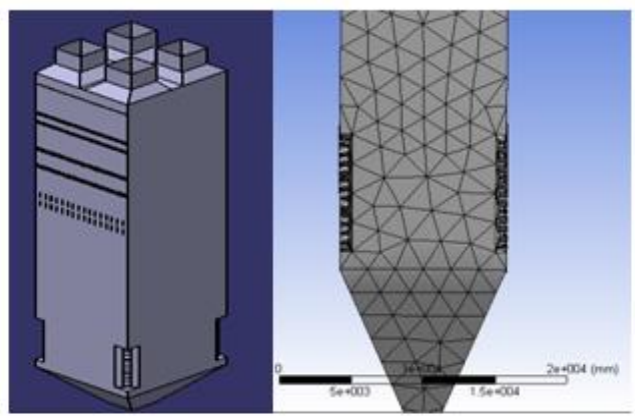

Fig 1 Furnace geometry and meshing

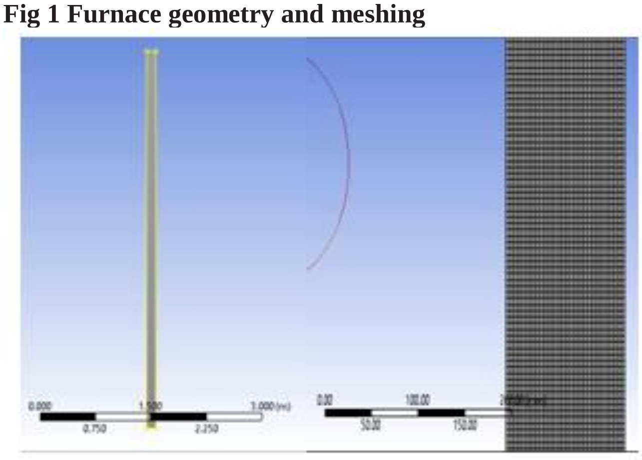

Fig 2 water wall geometry and meshing

Table 2 Proximity and ultimate analysis

Proximity analysis	
CONSTITUENTS	MASS FACTION PERCENTAGE
Moisture	4.10
Volatile matter	28.94
Ash	39.48
Fixed carbon	27.48
Ultimate analysis	
Moisture	4.10
Mineral matter	43.44
Carbon	41.86
Hydrogen	3.09
Nitrogen	1.52
Sulfur	0.34
Oxygen	5.66

Coal Particle Size = 70 µm (200 mesh)
Calorific value of the coal sample is 3480 kCal/K

THE BOUNDARY CONDITIONS

The boundary conditions considered for the present analysis are as follows:

Inlet conditions:

Mass flow rate:
Primary air flow: 230 T/hr
Secondary air flow: 440 T/hr
Fuel: 130 T/hr

Temperature:
Primary air flow: 90^{o}C
Secondary air flow: 300 ^{o}C
Fuel: 90^{o}C

Pressure:
Primary air flow: 260 mm WC
Secondary air flow: 100 mm WC
Fuel: 260 mm WC

Furnace pressure: - 15 mm WC
Out let pressure of boiler: - 40 mm WC
Walls: Adiabatic or constant wall temperature
Flow: No-slip condition at the walls; u = 0, v = 0, w = 0.
Temperature: Walls at the surfaces inside the combustion chamber are covered by the saturating steam tubes at constant temperature at T = 621.32 K
The boundary conditions considered for the water walls are as follows:

Water wall boundary conditions

Inlet: Pressure: 16.18 MPa
Temperature: 348.4^{o}C
Outlet: Pressure: 16.17 MPa
Temperature: 348.4^{o}C
Adiabatic flame temperature inside the furnace is assumed to be 1400 K which is estimated from CFD analysis and real time data.

ASSUMPTIONS

The problem is modeled with the following general assumptions:

1. The flow is steady and incompressible.
2. Variable fluid properties.
3. Turbulent Flow
4. Instantaneous combustion with the chemical reaction much faster than the turbulence time scale.
5. The steam temperature is assumed as the tube wall temperature.

The full three-dimensional Navier-Stokes equations are employed with five species transport equations.

III. Mathematical model:

The mathematical model is used here based on the commercial CFD code, FLUENT [15], where the gas flow is described by the time averaged equations of global mass momentum, enthalpy and species mass fraction. The particle phase equations formulated in Lagrangian form and the coupling between phases is introduced through particle sources of Eularian gas-phase equations. The standard k-ε turbulence model, single mixture fraction probability density function (PDF) and the P1 radiation models are used in the present simulations.

For the bulk of engineering combustion systems the mixing process proceeds much more slowly than the chemistry and as a result the mixing rate almost always determines the rate of combustion [11]. Therefore, for the predominant industry case of 'diffusion' or non-premixed combustion it normally suffices to solve a conservation equation for a mixing variable called the 'mixture fraction' in order to determine the temperature and concentrations of major species. In this study, a simplified coal combustion furnace is modeled using the non-premixed combustion model for the reaction chemistry. The following steps describe the method followed, after creating the required geometry.

1) A PDF table for a pulverized coal fuel using the pre-PDF preprocessor was prepared for medium volatile coal.
2) FLUENT inputs for non-premixed combustion chemistry modeling were estimated.
3) A discrete second phase of coal particles was defined.
4) Simulations were carried out first without involving reactions and discrete phase coal particles and then once the convergence is achieved, simulations were continued involving reacting discrete phase coal particles.

The composition in terms of atom fraction of H, C, N, O, along with the lower heating value and heat capacity of the fuel are defined using the data obtained from power plant. The fuel composition inputs were determined using proximate and ultimate analysis data provided. Table 2 summarizes the proximate and ultimate analysis data (db: drybasis; daf: dry-ash-free basis), which was used to derive the elemental composition of the volatile stream. The volatile release model is based on a single kinetic rate model [15,16] 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, which correlates rates of weight loss with temperature.

As in most practical fossil-fuel combustion simulations, the incompressible form of the equations of motion using a finite volume form of the discretization equations are solved with

SIMPLE-based approaches. It is also assumed that the flow field is at a steady-state and the solution procedure is simplified by solving a steady-state form of equation of motion. For many combustion processes, radiation is not only the dominant energy transport mechanism but also one of the most complex problems. The accuracy of the radiation calculation depends on a combination of the accuracy of calculation method and the accuracy to which the properties of the radiating media and surrounding walls are known [17]. The P1 radiation model is used to account for the exchange of radiation between gas and particulates, with cell based WSGGM model (weighted-sum-of gray-gases model), which specifies a composition dependent absorption coefficient. All thermodynamic data including density, specific heat, and formation of enthalpies are extracted from the pre-PDF chemical database.

IV. VALIDATION OF CFD ANALYSIS IN FURNACE ZONE

The predicted temperatures at the furnace exit as estimated using CFD is found to be 1385K, while the live data as recorded for the same conditions was reported as 1430K. The predicted molar fraction of oxygen (%) and carbon dioxide (%) at the furnace exit are 0.9% and 14% respectively from CFD analysis. The measured molar fractions of oxygen (%) and carbon dioxide (%) at the furnace exit were found to be 7% and 13% respectively. The error in estimation of temperature is 3.3% while the deviations for the oxygen and carbon dioxide mass fractions are 14% and 7.14% respectively. Since the estimated values using CFD is in close agreement with the recorded live data in the boiler, CFD analysis holds good and was further used in the subsequent analysis.

Table 3 validation for the CFD

	Plant measurement	CFD
Temperature (K)	1430	1382
Oxygen (% molar fraction)	7	6
Carbon dioxide (% molar fraction)	13	14

V RESULTS AND DISCUSSION

The pulverized coal supported with combustion air and flue gas velocity distribution across the cross sections along the furnace height is shown in Fig 3.The coal particulates with combustion air enters the combustion zone with an average velocity of 45 m/s and the flue gas is found to flow with an average velocity of 26 m/s at the exit of the combustion zone.

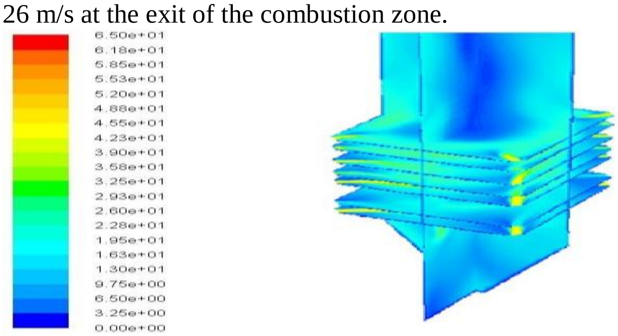

Fig 3 Velocity magnitude

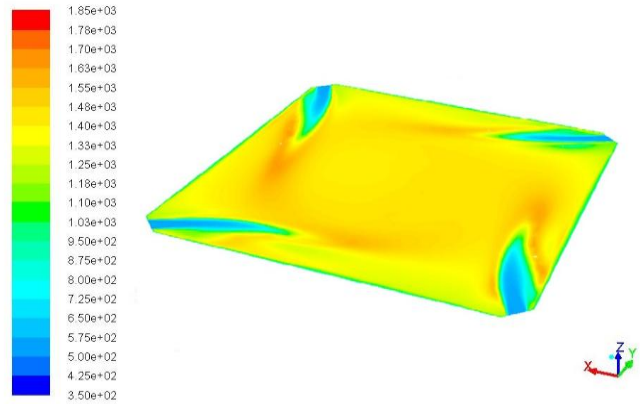

Fig 4 Contours of static Temperature

The presence of tangential fired system generates a swirling fire ball at the center of the combustion zone which is shown in Fig 4. The swirling flow is stronger at the lower level approximately 13 m from ground level as compared at 30m from the ground level. The maximum temperature of 1850 K is found to exist at the central part of the furnace. In the upper region (approximately around 25m to 30m), the swirling flow is remarkably reduced as seen in Fig 5.

The path lines as observed in Fig 5 indicates the particulates dispersing upwards leading to reduced swirling movement by virtue of slightly negative draft maintained above the combustion zone. The streamlines and trajectories show very complicated three-dimensional flow characteristics which promote the mixing of the air and coal particles and thereby enhancing heat transfer via bulk motion. The flows located near the burners show more activity than in other locations.

The flue gas and coal particles from the higher burners pass around the surface of the fire-ball region. As a result, the residence times of the flue gas, and coal particles injected from the higher burners are shorter as compared to the flue gas and coal particles injected from the lower burners. The average residence time of the flue gas within the boiler is 2.7 seconds. Coal de volatilization and char combustion take place while the coal particles are traveling around the furnace.

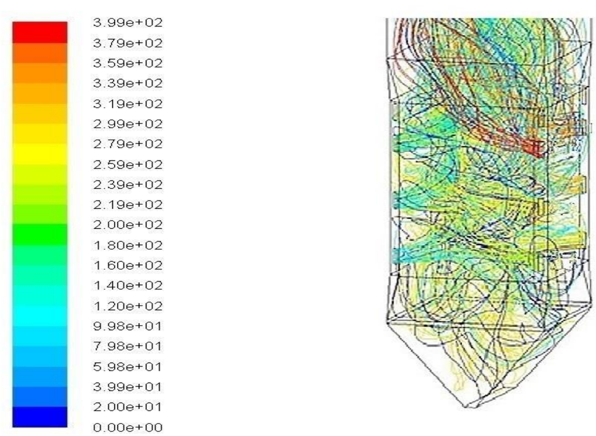

Fig 5 Path lines of the Flue gas

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Residence time and turbulence are always considered together: The more the turbulence inside furnace, the longer the residence time for the coal particles. It is obvious that the residence time depends on the location of the burner. The residence time decreases with increasing elevation of the burner.

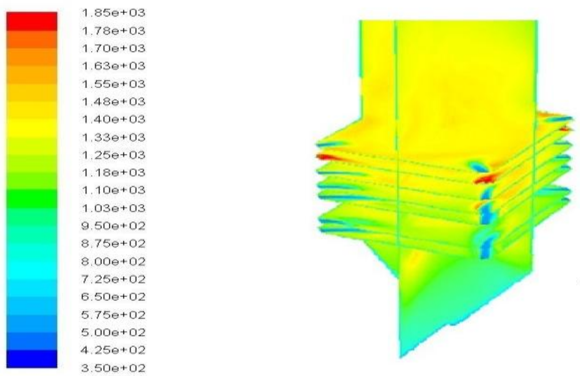

Fig 6 Temperature fields in a coal fired furnace

The temperature distribution across the furnace cross section is shown in Fig 6. The temperature of the pre-heated air entering the tangential burners is found to be at 343 K. The temperature of the flue gas is found to exist at a temperature of 1630 K at the center of the furnace except at few locations probably due to reverse flow of flame which acts as a source of ignition to the incoming fresh coal. As the flue gas moves upward, the temperature of the flue gas decreases due to the heat transfer to the surrounding water walls. The flue gas leaves the boiler furnace with an average temperature of 1,383 K. The high temperature zones are closely related to NO_x formation which is dependent on local temperature.

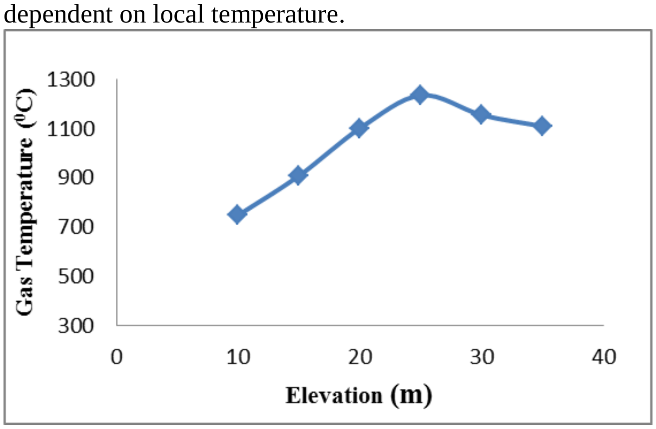

Fig 7 Area weighted average temp along the elevation of combustion zone

Fig 7 shows the temperature variation along the elevation inside the combustion zone. The gas temperature is found to increase steadily with elevation and a peak temperature is noticed at approximately 25m. The burners inside the furnace are restricted up to 25m and the temperature is found to drop marginally thereafter. A strong swirling motion with induced turbulence is observed up to 25m. The peak temperature of 1236^0 C is observed near the burners.

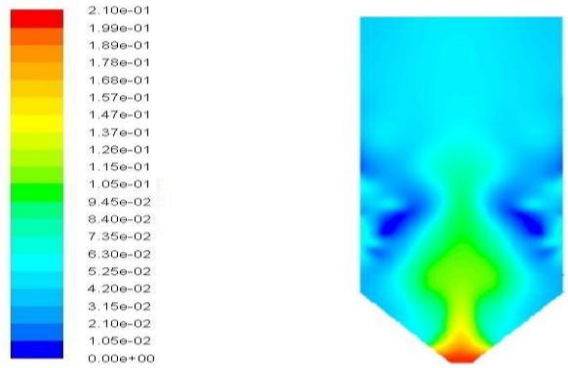

Fig 8 Oxygen distribution in tangential fired boiler

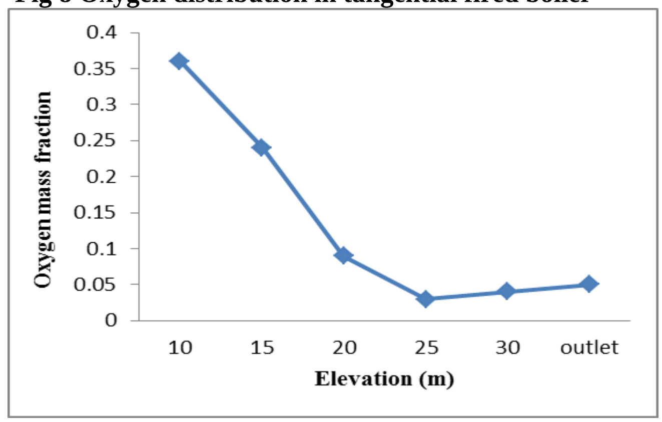

Fig 9 Mass weighted average of oxygen mass fraction along the furnace elevation

The mass fraction of oxygen presence inside the furnace is depicted in Fig.8. The oxygen concentration in the furnace is relatively higher near the burners. The available oxygen is found to be quickly consumed during the combustion processes. Due to this, the oxygen mass fraction rapidly decreases across the combustion chamber. Further the oxygen content is found to be maximum near the hopper, there is a proportionate drop in oxygen content near the burner.

Fig 9 shows the oxygen mass fraction variation along the elevation of the combustion zone. With increase in elevation, the mass weighted average of oxygen increases up to 25 meters; this is due to utilization of available secondary air at higher elevations. Further with increase in the elevation, the mass weighted average of oxygen remains constant because of the complete combustion of the coal.

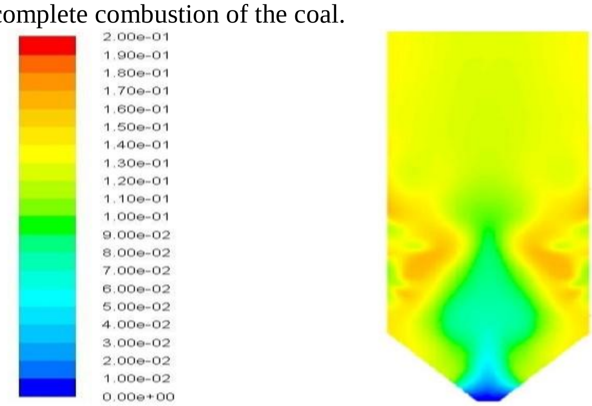

Fig 10 Carbon dioxide distribution in tangential fired boiler

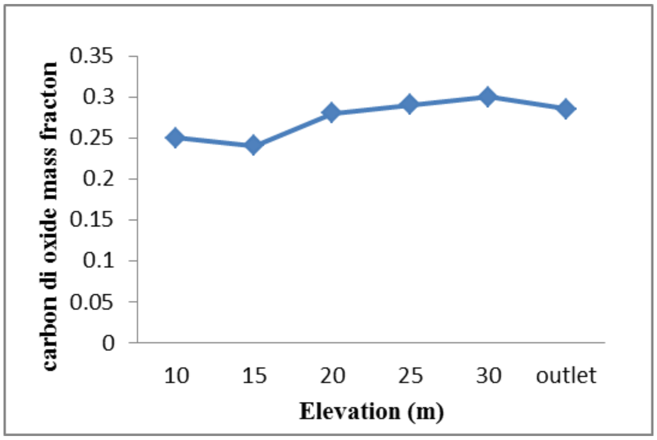

Fig 11 Mass weighted avg. of carbon dioxide mass fraction along the furnace elevation

The carbon dioxide distribution across the cross sections is shown in Fig 10. As carbon dioxide being a byproduct of combustion, the content of carbon dioxide is found to be maximum near the burner and a systematic pattern is observed across the combustion chamber with marginal drop with elevation. Carbon dioxide content is observed to be minimum near the hopper zone

Fig 11 shows cross sectional mass weighted average of carbon dioxide variation along the elevation in the combustion zone. As the elevation increases, the mass weighted average of carbon dioxide increases, this is due to rapid utilization of secondary air. Beyond 20m of elevation the mass weighted average of carbon dioxide is found to increase marginally due to complete combustion.

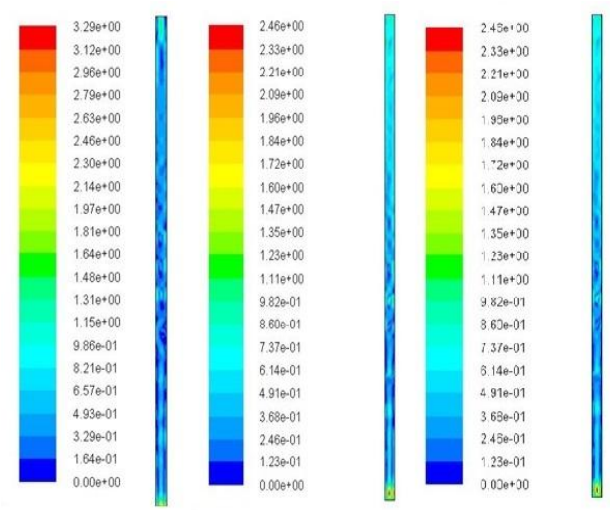

Fig 12 Contour of velocity (mixture) at 900°C, 1000^0 C and 1100^0 C

The variation of velocity of two phase mixture at 900°C, 1000°C and 1100°C are shown in Fig 12. The velocity of the mixture is found to increase with increasing flue gas temperature. The possible reason for local acceleration could be due to enhanced two phase formation across the tube leading to increased buoyancy effect observed along the tube.

The variation of vapor volume fraction at 900°C, 1000°C and 1100°C are shown in Fig 13 respectively. The vapor volume fraction of the mixture is found to increase significantly with increasing flue gas temperature. The profile observed indicates a definite phase transformation occurring inside the tube with increase in flue gas temperature inside the furnace.

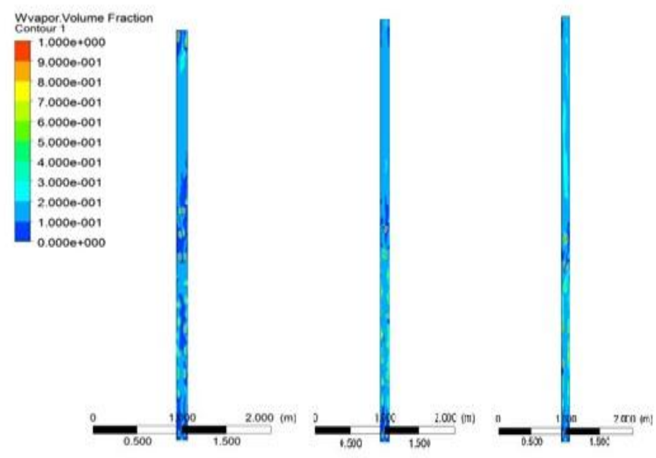

Fig 13 Water vapor volume fraction (mixture) at 900°C, 1000^0 C and 1100^0 C

Table 4 Heat transfer coefficients comparison

Method	**Heat transfer coefficient (W/m^{2}K)**
Kandiker	9460
Shah	9157
CFD	9477

The CFD simulation results are compared with correlations obtained using Shah and Kandiker for validating the simulation results as shown in Table 4. A close agreement with an error of less than 4% is observed between the CFD analysis estimated heat transfer coefficients. While Shah correlation showed 3.3 % deviation and Kandiker correlation showed much lower deviation of 0.179%.

CFD simulation for the different wall temperatures has been carried out. The values for particular case is tabulated in Table 5.It can be observed that the heat transfer coefficient decreases with increase in temperature of the furnace wall.

Table 5 Heat transfer coefficients for different wall temperatures

Method	**h_{tp} (W/m^{2}K)**
CFD(wall at 900^0 C)	9477
CFD (wall at 1000^0 C)	9728
CFD (wall at 1100^0 C)	10345

VI. CONCLUSION

The critical parameters inside the furnace were evaluated using CFD and compared with the recorded live data in a 210 MW tangential fired coal boiler. The conclusions drawn from the present analysis are summarized below.

1. The CFD simulations of tower type boiler using fluent are found to be in close agreement with correlations published in literature. The predicted molar fractions of oxygen and carbon di oxide at the furnace exit are 6% and 14% respectively. The measured molar fractions of oxygen and carbon di oxide at the furnace exit are 7% and 13%. The error obtained for temperature is 3.3% while the deviations for the oxygen and carbon di oxide mass fractions are 14% and 7.14% respectively.
2. The area mass weighted temperature steadily increases up to 25 meters and estimated to be 1357^{o}C.
3. As the elevation increases, the mass weighted average of oxygen mass fraction increases up to 25 meters, further increase in elevation leads to constant oxygen mass fraction.
4. Kandiker and Shah correlations were used in the evaluation of heat transfer coefficients and found to be 9460 W/m^{2}K and 9157 W/m^{2}K respectively. While the CFD analysis yielded a value of 9477 W/m^{2}K. Since the estimated and CFD values fall in the range more than 3000 W/m^{2}K, this certainly indicates a phase transformation phenomenon. As the working fluid flows along the water wall. Shah correlation conceded a 3.3% deviation and Kandiker correlation had a deviation of 0.179%.
5. Heat transfer coefficients for different wall temperatures are evaluated using CFD. At 900^{0}C, 1000^{0}C and 1100^{0}C the heat transfer coefficients obtained are 9477 W/m^{2}K, 9728 W/m^{2}K, 10345 W/m^{2}K respectively.
6. The residence time of particles as observed from particle trajectories indicates that at lower elevations, the residence time is more as compared to fuel particles from higher elevations.

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