The Journal of CPRI,
Vol. 12, No. 3, September 2016 pp. 625-636

CFD modelling of the blended coal combustion in a typical 210MW Indian boiler

Arun Kumar K H*, Saravanan V**, Kumar R K** and Shekhar Kumar M***

The computational fluid dynamics (CFD) assessment was carried out for the combustion of pure Indian coal and the blends of Indian/imported coals at various proportions in a typical 210 M We Indian boiler. The input fuel mass flow rate was calculated in various cases to give the same thermal input to the boiler. The various sub models used for the CFD assessment has been described in the paper. The velocity and temperature profiles of the gas phase, combustion profile of the particles, heat flux distribution to the walls of the boiler and also the thermal efficiency of the boiler were assessed in the present work. It was found that the particle and fluid dynamics play a major role in the heat flux distribution in the boiler. The Indian and imported coal blend proportion of 80/20 showed good thermal efficiency compared to the pure Indian coal and other blend proportions.

Keywords: *Blended coal, CFD, Indian boiler, heat flux distribution, pre-mixed blending*

NOMENCLATURE:

ρ_A	-	Density of species A, kg/m^3
u_A	-	Velocity of creation of species A, m/s
S_A	-	Rate (kg/m^{3}s) of creation of species A from a source in the chemical reaction.
μ	-	Viscosity-m/s^2
λ	-	Thermal conductivity of the fluid, W/m-K
Q_R	-	Rate of heat release from chemical reaction.
H	-	Total Enthalpy.
h	-	Static enthalpy.
T_{ref}	-	Reference temperature
Cp	-	Specific heat.
C_D	-	Drag coefficient.
v_f	-	Velocity of fluid
v_p	-	Velocity of particle
ρ_f	-	Density of fluid.
R_e	-	Reynolds number.
d_p	-	Diameter of particle.
Rp	-	Radius of the coal particle.
Tg	-	Far-field gas temperature in the boiler.
P	-	Local pressure.
P_A	-	Atmospheric pressure.
V	-	Mass of volatiles.
V_f	-	Final yield of volatiles.
k_v	-	Rate constant.
T_p	-	Temperature of coal particle.
k_c	-	Chemical rate coefficient.
T_p	-	Uniform temperature of particle.
ε_p	-	Emissivity of particle.
σ	-	Stefan Boltzmann constant.
I	-	Radiative flux at the location of the particle.
f_v	-	Fractional yield of volatiles.
N_u	-	Nusselt number.
P_r	-	Prandtl number.
y'	-	Scattering direction vector.
y	-	Path length.
a	-	Absorptivity.
n	-	Refractive index.
r	-	Scattering coefficient.
T	-	Local temperature.
ϕ	-	Phase function.
Ω'	-	Solid angle.

* SRF, Materials Technology Division, Central Power Research Institute, Bengaluru-560080, India. E-mail:arunkumar_srf@cpri.in
**Joint Director, Materials Technology Division, Central Power Research Institute, Bengaluru-560080, India. E-mail: saran_cpri@cpri.in
*** Additional Director (Retd.), Materials Technology Division, Central Power Research Institute, Bengaluru-560080, India.

1.0 INTRODUCTION

The pulverized coal fired boilers in India were originally designed to burn Indian coals for enabling the power plants to operate at maximum efficiency. However, in many cases, these coals are no longer fired due to the short fall of domestic coal supply in the country. The blended coal firing is found to be one of the promising methodologies to meet the coal shortage and the design coal requirement in the Indian power plants. The blended coal firing involves many advantages other than meeting the short fall of domestic coal, that includes [1] reduction in fuel costs, emission control limits and the extension of the range of acceptable coals. However, burning coal blends is not always straightforward and may produce unanticipated and undesirable consequences as their performance may not be interpolated linearly from that of the parent coals [2]. The study made by Carpenter [3] indicates that some of the blended coal properties are additive and interpreted from the parent coal behaviors and some are non-additive. Carpenter has made a detailed review on the studies made by many researchers and concluded that some of the quantitative properties like proximate, ultimate parameters and heat value can generally be predicted from component coals with few exceptions. The interaction between the different ranks of coal components during combustion may even alter the quantitative parameters (example ash content). The sulphur oxide released by high sulphur bituminous coals may get absorbed by the alkali content of sub-bituminous coals and retained as sulphate in the resultant ash product. This will increase the ash content in the blended coal than the predicted value from component coals. Carpenter has reported that the qualitative parameters viz. grindability, ash fusibility and reactivity were mostly non-additive. The reasons for the non-predictability of the blend properties were laid on the rank difference between the coals and the interaction between the constituents of the component coals. Nevertheless, several authors have studied the combustion characteristics of coal blends [4-7] but no general consensus has been reached on the interaction between component coals. While SSu et al stated that the high volatile coals could improve the carbon burnout, ignition and flame stability in the blends of higher rank coals [8], T.Beelay et al have reported that there was a decrease in the overall burnout of the blend compared to component coals [9]. The overall views of these studies indicate that the properties and behavior of the coal blends is complex which cannot easily be predicted from the properties of component coals.

The blend ratio is one of the critical aspects in respect of obtaining better techno-economic efficiency of the power plants. CFD is one of the powerful tools, which can be used to study the combustion phenomena happening inside the boilers. In the present work CFD was used to assess the steady state temperature profile, particle dynamics, volatile release rate, heat flux distribution, etc. to arrive at an optimum blend ratio in which the best performance of the boiler can be achieved. In the present work CFD simulations were carried out for four cases in which the first case is pertaining to the combustion of pure Indian coal and the other three cases are pertaining to the blends of Indian coal with an imported coal (Indonesian coal) of blend proportions 90/10, 80/20 and 70/30. The strategy of selecting the input parameters required for CFD modeling is given in the experimental section.

2.0 EXPERIMENTAL WORK

The CFD simulations were carried out for four cases and are given below:

CASE A: Indian coal

CASE B: 90% Indian and 10% Imported Coal

CASE C: 80% Indian and 20% Imported Coal

CASE D: 70% Indian and 30% Imported Coal

A typical BHEL designed 210 MWe boiler geometry was chosen for this study and the configurations of the same are given in Figure 1 and Figure 2.

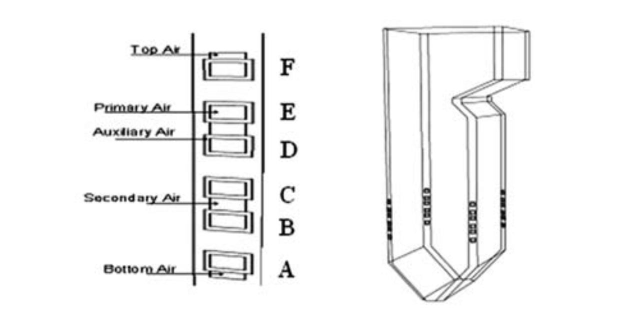

FIG. 1. GEOMETRY OF THE INDIAN 210 MW TANGENTIALLY FIRED BOILER

Every power plant boiler is designed for a range of properties of coal, and a typical coal which is meeting this range of properties is called as "design coal". An Indian coal which is meeting the design coal properties of the 210 MWe boiler has been chosen for the CFD simulations. Also for studying the blended coal combustion behavior, a typical Indonesian coal was taken and the properties of both the Indian and imported coals are given in the Table 1.

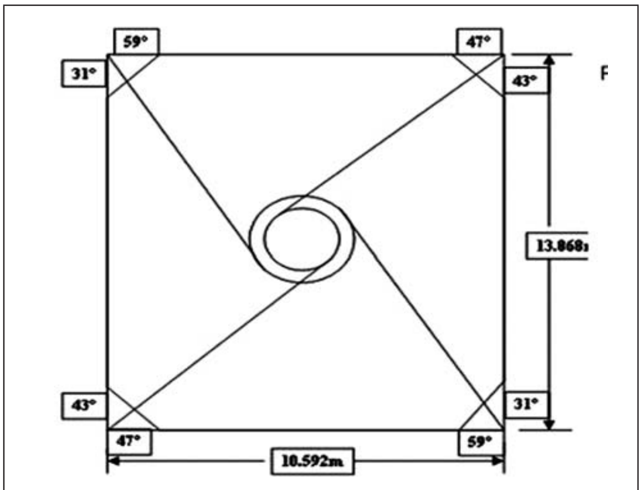

FIG. 2. TANGENTIAL FIRING CONFIGURATION

The 210 MWe pulverized coal boilers are operating generally with 35% overall efficiency and the heat input pertaining to the same is 600 MW_{th}. In all the above four cases, the heat input is maintained same and the mass flow rate of the coal/blended coal was accordingly adjusted. The stoichio metric air quantity was calculated based on the ultimate parameters of both the Indian and imported coals based on the blend proportions and also on the mass flow of the input coal/coal blend (Table 1). The total input air is the addition of stoichiometric quantity and 25% excess air. The particle size was maintained 60 µm uniform diameter to avoid the complications of particle size effect towards the CFD results.

The geometry of 210 MW boiler used in this work was not modeled for super and re-heaters to avoid more complexity in the geometry as the present work is only to study the combustion behavior of the coal blends.

3.0 CFD MODELING OF COAL COMBUSTION

3.1 Gas Phase simulation

TABLE 1

PROPERTIES OF THE INDIAN AND IMPORTED COAL

Properties of coal	Imported Coal	Indian Coal
Proximate analysis (%)		
Moisture	17.7	8.3
Volatile matter	42.7	24.1
Fixed Carbon	29.8	26
Ash	9.8	41.6
Ultimate analysis (%)		
Carbon	57.1	36.6
Hydrogen	4.59	2.78
Nitrogen	1.19	1.39
Sulphur	1.09	0.69
Oxygen	8.53	8.64
Other parameters		
Gross Calorific Value (kcal/kg)	5670	3470
Maximum Volatile Yield	1.25	1.25
Activation Temperature (T_c) for char (K)	10000	8500
Pre exponential factor (A_c) for char $K.m^{-2}s^{-1}$	49.7	497

The gaseous field is described by the transport equations of the continuum phase. Three-dimensional, steady-state Reynolds averaged Navier-Stokes equations closed by the k-ε turbulence model are solved for the turbulent gas flow, including mass, momentum, turbulence kinetic energy, turbulent dissipation rate, enthalpy, and a number of gaseous species mass fractions. The species conservation equation for a Newtonian fluid flow can be derived [10] as

$$\frac{\partial}{\partial t}(\rho_A) + \nabla\cdot(\rho_A u_A) = S_A \quad \text{....(1)}$$

Similarly, the momentum and energy equations can be written for the mixture as

Momentum

$$\frac{\partial}{\partial t}(\rho u) + \nabla\cdot(\rho u u) = -\nabla_p + \nabla\cdot\{\mu[\nabla_u + (\nabla_u)^T]\} \quad \text{.... (2)}$$

Energy

$$\frac{\partial}{\partial t}(\rho H) + \nabla\cdot(\rho u H) = \frac{\partial p}{\partial t} + \nabla\cdot(\lambda\nabla T) + \nabla\cdot\{\mu[\nabla_u + (\nabla_u)^T]\}\,u + Q_R \quad \text{...(3)}$$

The total enthalpy H here is defined as

$$H = h + \frac{1}{2u^2} \quad \text{.... (4)}$$

The static enthalpy is evaluated in terms of specific heat as

$$h(T) = \int_0^T [C_p(T^1)]dT^1 - \int_0^{T_{ref}} [C_p(T^1)]dT^1 \quad \text{..(5)}$$

The static enthalpy is taken to be zero at reference temperature. This definition is extended for a mixture of gases also assuming that the constituent species are thermally perfect, i.e., their static enthalpies are functions only of temperature.

3.2 Particle Transport

In this model, two coal particle groups are employed to track the individual component coals (Indian Coal and Imported Coal) separately. Rather than being modelled as an extra Eulerian phase, two distinct injections of particles are treated as dispersed phases in a Lagrangian way, by which particle behaviours are tracked along the discrete particle trajectories without considering physical interaction between particles in gas phase.

The forces acting on the particle which affect the particle acceleration include drag force, pressure gradient force, virtual mass force, buoyancy force and turbulent dispersion etc. In this model, only the drag force and turbulent dispersion are modelled. The drag force is calculated by,

$$F_D = \frac{1}{8}\pi d^2 \rho_f C_D |v_f - v_p|(v_f - v_p) \quad \text{....(6)}$$

The drag coefficient C_D is given by modified Schiller and Neumann,

$$C_D = \max\left(\frac{24(1+0.15 R_e{}^{0.687})}{R_e}, 0.44\right) \quad \text{....(7)}$$

3.3 Devolatilisation

In general, coal combustion is considered as a three-stage process: the devolatilisation of a raw coal particle, followed by the gaseous combustion of the volatiles and the oxidation of the residual char in the gas phase. When a coal particle is subjected to intense heating, the volatile components first evolve from the particle, and then subsequently burn into gas phase. This process, the evolution of volatile gases from the coal, is termed as devolatilisation. The volatile matter is released from a temperature of about 800 K [10]. In the present study dealing with coal blends, the blends combustion involves two chemically different fuels. Two component coals with different properties will undergo individual combustion reactions, including devolatilisation, gaseous combustion and char oxidation.

$$\frac{dV}{dt} = k_v(v_f - V) \quad \text{.... (8)}$$

The rate constant k_v is expressed in Arrhenius form as

$$k = A\, e^{\frac{-E}{T_p}} \quad \text{.... (9)}$$

v_f is required as input data, the temperature of the coal particle is obtained through a Lagrangian particle trajectory.

3.4 Char Oxidation

The second coal pyrolysis product is char. Char combustion is a much slower process than devolatilisation, and it therefore determines the burnout time of the coal in the raceway. Char oxidation is modelled using the model proposed by Field [11], where in this model, a char particle is considered to be a spherical particle surrounded by a stagnant boundary layer through which oxygen must diffuse before it reacts with the char. The oxidation is assumed to be limited by the diffusion of oxygen to the external surface of the char particle and by the effective char reactivity. The rate of diffusion of oxygen is given by k_d (P_g P_s), where P_g is the partial pressure of oxygen in the boiler gases far from the particle boundary layer and P_s is the oxygen pressure at the particle surface. The value of k_d is given by

$$k_d = \frac{2.53*10^{-7}}{R_p}\left(\frac{T_p+T_g}{2}\right)^{0.75}\frac{P_A}{P} \quad \text{.... (10)}$$

The char oxidation rate unit area of the particle as a first order reaction is given by kcPs, the chemical rate coefficient is given by

$$k_c = A_c T_p e^{\frac{-T_c}{T_p}} \quad \text{.... (11)}$$

The values of Arrhenius constants depend on the type of the coal and specified as input parameters in the calculations. The overall char reaction rate of a coal particle is given by

$$(k_c^{-1} + k_d^{-1})^{-1} P_g 4\pi R_p^2 \frac{P}{P_A} \quad \text{....(12)}$$

TABLE 2

INPUT PARAMETERS	CASE A	CASE B	CASE C	CASE D
	INDIAN COAL	90% INDIAN COAL	80% INDIAN COAL	70% INDIAN COAL
Mass of Indian Coal Input (t/h)	149	126	106	87
Mass of Imported Coal Input (t/h)	0	14	26	37
Primary Air (t/h)	300	300	300	300
Secondary Air (t/h)	556	555	554	554
Total Heat Input (MW)	600	600	600	600

3.5 Heat Transfer

The radiative heat transfer, concerned with coal and char, is one of the most significant features of coal combustion compared with gaseous and liquid combustion. The net radiative power absorbed by a particleis calculated by,

$$q_r = 0.25\varepsilon_p \pi d_p^2 \left(I - \sigma T_p^4\right) \quad \text{....(13)}$$

The value of the particle emissivity ε_p is expected to change as pyrolysis proceeds, i.e., it varies depending upon the mass fractions of coal and char. The present model assumes a linear variation in ε_p from the raw coal value ε_p (coal) to the value for char ε_p (char). That is,

$$\varepsilon_p = (1 - f_v)\varepsilon_p(\text{coal}) + f_v \varepsilon_p(\text{char}) \quad \text{....(14)}$$

Typical values for ε_p are 1.0 for coal and 0.6 for char.

Another significant heat transfer mode is convection. It is assumed that the combustion of volatiles releases heat into the gas phase and the oxidation of char releases heat into the coal particles. Convective heat transfer due to temperature difference between the fluid and a particle is calculated using a semi-empirical correlation for the Nusselt number according to Ranz-Marshall (1952) [12],

$$N_u = 2 + 0.6\, R_e^{0.5} Pr^{0.33} \quad ....(15)$$

The radiative heat transfer being a dominant

mode of heat transfer and is governed by the radiative transfer equation (RTE) which for an absorbing, emitting, and scattering medium at position r in the direction y is given by

$$\frac{dI(r,y)}{dy} + (a + \sigma_s) I(r,y) = an^2 \frac{\sigma T^4}{\pi} + \frac{\sigma_y}{4\pi} \int_0^{4\pi} I(r,y)\, \phi(y \cdot y')\, d\Omega' \quad ....(16)$$

The solution of above integro-differential equation is very complex and consumes enormous computational time. Several approximate methods have been developed to deal with radiative heat transfer in practical combusting systems; these have been reviewed in detail by Viskanta and Menguc [13]. In the present study, the discrete transfer radiation model (DTRM) isused. The main approximation in this model is that the radiation leaving the surface element in a certain range of solid angles can be approximated by a single ray.

3.6 Sub-models

The discrete transfer radiation model proposed by Shah [14] was used in the present work. The particle heat transfer was modeled using Ranz-Marshall model [15] and the particle drag was accounted by

Schiller-Neumann [16]. Eddy Dissipation Model [17] was used for the gaseous combustion. The mathematical interpretation of coal particle combustion sequence was conceptualized from methods given by Smith [18]. The CFD calculations were performed using ANSYS-CFX V.14.0 commercial software.

4.0 RESULTS AND DISCUSSIONS

In the pulverized coal boiler, the burners are arranged in an angle of 43°/47° and 47°/43° in one diagonal and 31°/59° and 59°/31° in

TABLE 3

Flue Gas Exit Temperature (^OK)		CASE A	CASE B	CASE C	CASE D
		927	**920**	**900**	**925**
Heat Carried away by flue gases (%)		32.9	32.5	31.2	32.7
Heat Flux Distribution (MW/m^2)	LHS	41	43.2	49.1	41.7
	RHS	42.4	40.4	51.2	42.3
	FRONT	65.7	67.5	66.3	65.1
	REAR	57.3	65.8	67.2	66.2
	BOTTOM	5.9	5.8	5.9	5.7

another diagonal of the BHEL designed 210MWe boiler. This creates a static mixer arrangement for the incoming fuel and rotates the resultant fire ball vortex in one direction. This arrangement is meant for creating heavy turbulence inside the boiler for the effective mixing of solid fuel particles and oxygen and also equal heat flux distribution to all the water walls. However, as the boiler geometry is not symmetric and flow is exiting out of the boiler in one direction, the dissimilarity in heat flux distribution to the water walls (Left, Right, Front, Rear, Bottom and Top) is unavoidable. The thermal efficiency is the amount of heat energy absorbed out of the total input energy by the heat exchanger coils. Higher the amount of heat energy carried by the flue gas indicates the lower the amount of heat energy absorbed in the heat exchanger coils (heat sinks) and lower the thermal efficiency. The thermal efficiency of the boiler is normally about 85 to 90%. In the present work, the super heater, re-heater and economizer heat sinks were not modeled for reducing the complexity of work. Only water walls were modeled as a heat sink with the fixed temperature of 350°C. The amount of input heat energy in

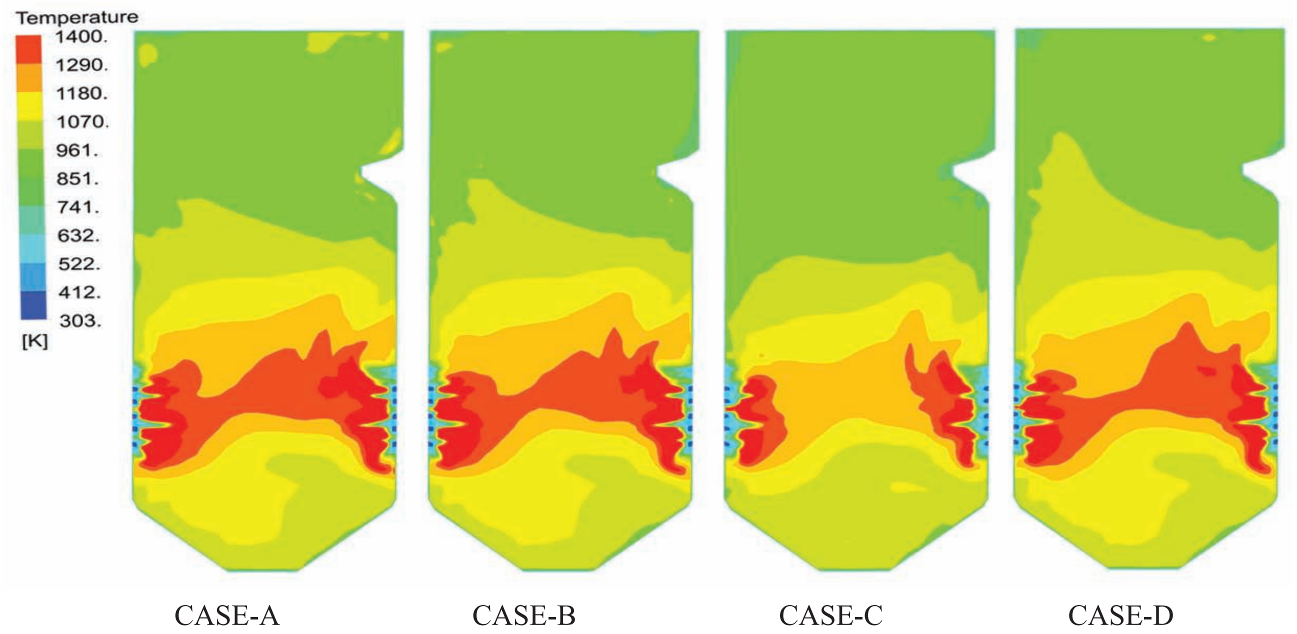

FIG. 3. TEMPERATURE PROFILE ON THE PLANE ALONG THE DIAGONAL OF THE 210 MW BOILER

the case of CASE A, B, C and D are equal and 600 MW_{th} respectively. The 600 MW_{th} of all the cases are from the fuels and the additional energy is the enthalpy of the input primary and secondary air. The calculated air input is given Table 2. The calculated values of air input were more or less same in all the four cases and as a result of the same, the velocity profiles of the gas phase are observed to be same in all the cases as given in Figure 4. The ash mass fraction data given in Figure 5 indicates that all the particles were almost combusted in all the cases irrespective of the variation in the blend composition. The Left Hand Side (LHS), Right Hand Side (RHS), Front Side (FRONT), Rear Side (REAR), Bottom Side

(Bottom) of the boiler geometry is given in Figure 6 and Figure 7. The distribution of heat flux to these sides for all the four cases are given as bar charts in Figure 8 to Figure 11. The heat flux distribution and the heat absorption profiles were found to be different in different walls as the flow in the boiler is not symmetric The FRONT and REAR walls absorbed more heat compared to LHS, RHS and bottom S-panel walls. As the FRONT and REAR walls are lengthier than LHS and RHS walls, the impact residence time of the flow would be more in respect of FRONT and REAR walls compared to LHS and RHS walls. This has resulted in the increased heat absorption in the FRONT and REAR walls compared to LHS and RHS walls. The S-panel absorbed minimum heat as the flow is in the upward direction and most of the flow was not impacting on the S-panel walls. It is observed that Case C (80/20 blend) show maximum absorption of heat energy to the water walls (239.7MW) and the Case A (Indian Coal) showed minimum absorption of energy to the water walls (212.3 MW) and the other cases, Case B (90/10 blend) and Case D (70/30) showed the values 222.7 MW and 221 MW respectively. This is supplemented by the reduction in the flue gas exit temperature at goose neck, where Case C showed minimum temperature (Table 3 and Figure 3), i.e. 900°C and the Case-A showed maximum temperature (927°C). This indicate that the Case C in which the blend proportion of 80% Indian Coal and 20% Imported Coal showed better thermal efficiency than the Indian coal and other blend compositions.

TABLE 4

	PARAMETERS (t/h)	CASE A	CASE B	CASE C	CASE D
PROXIMATE PARAMETERS	Moisture	12.4	12.9	13.4	13.8
	Volatile matter	35.9	36.3	36.7	36.8
	Fixed Carbon	38.7	36.9	35.3	33.7
	Ash	62.0	53.8	46.5	39.8
ULTIMATE PARAMETERS	Carbon	54.5	54.1	53.7	53.0
	Hydrogen	4.14	4.15	4.15	4.12
	Nitrogen	2.07	1.92	1.78	1.65
	Sulphur	1.03	1.02	1.02	1.00
	Oxygen	12.87	12.08	11.38	10.67

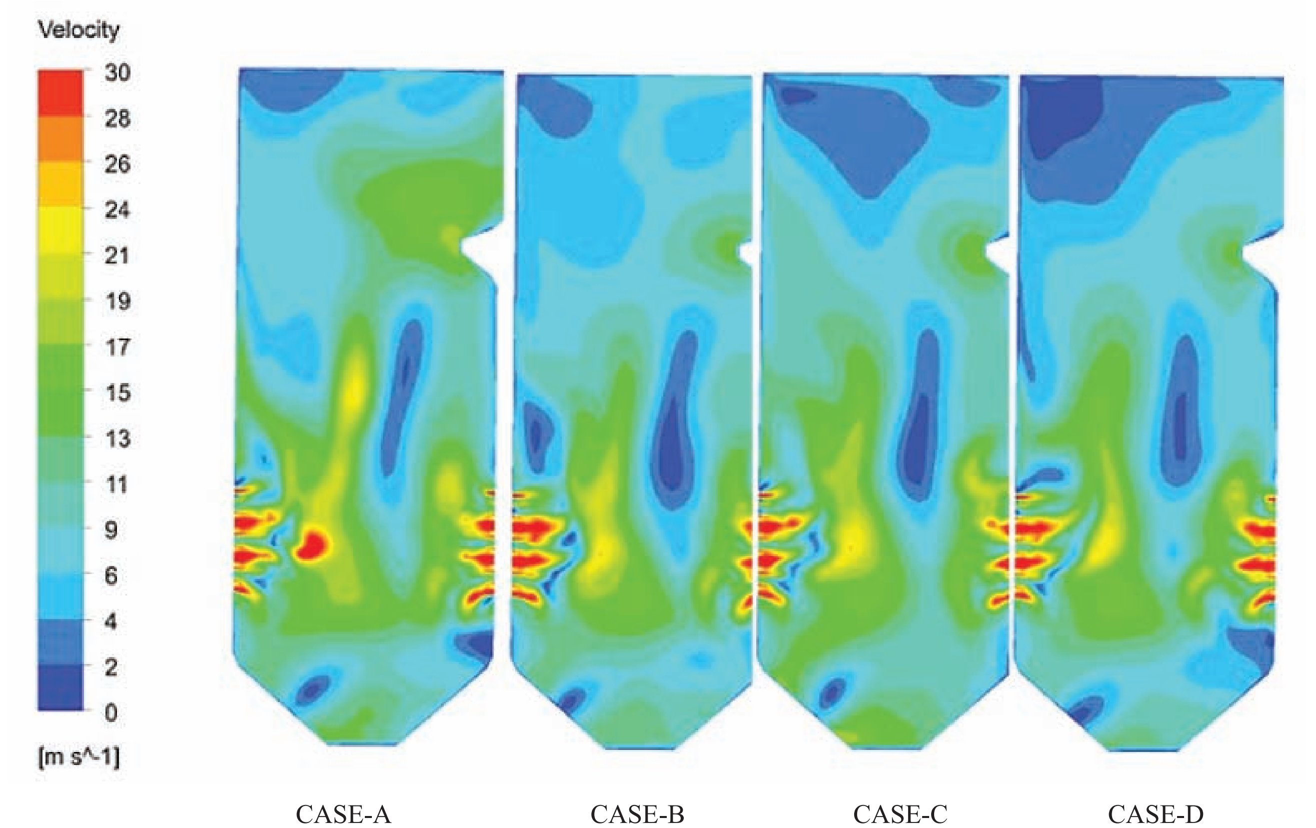

FIG. 4. VELOCITY PROFILE ON THE PLANE ALONG THE DIAGONAL OF THE 210 MW BOILER.

This is due to the decrease in ash content from pure Indian coal to 70% Indian coal and 30% Imported coal combination. The ash present in the boiler absorbs heat energy for its sensible heating. The quantum of heat absorbed is proportional to the amount of ash present in the boiler. If the ash content is reduced (62 to 39 t/h) the proportional heat energy will be available for the walls to get absorbed. The Table 4 indicates the reduction in ash content when the imported coal content is increased and this caused the reason for the high absorption of heat in the CASE C compared to pure CASE A and CASE B. However, there is a reduction in heat absorption in the CASE D and this might be due to the delay in the combustion of high carbon content of imported coal which is supplemented by the temperature profile of CASE D given in Figure 3.

However, the values of heat absorption in different cases are generally specific to the input coal properties and other operating conditions like the amount of input air quantity, etc.

Any change in the coal property or the operating conditions will change the results. It is inferred that this study is only a guideline for assessing the combustion behavior of coal and coal blends in utility boilers for optimizing the process parameters like blend ratio, etc. and the CFD assessment to be carried out for every specific case with standard conditions to obtain the required result.

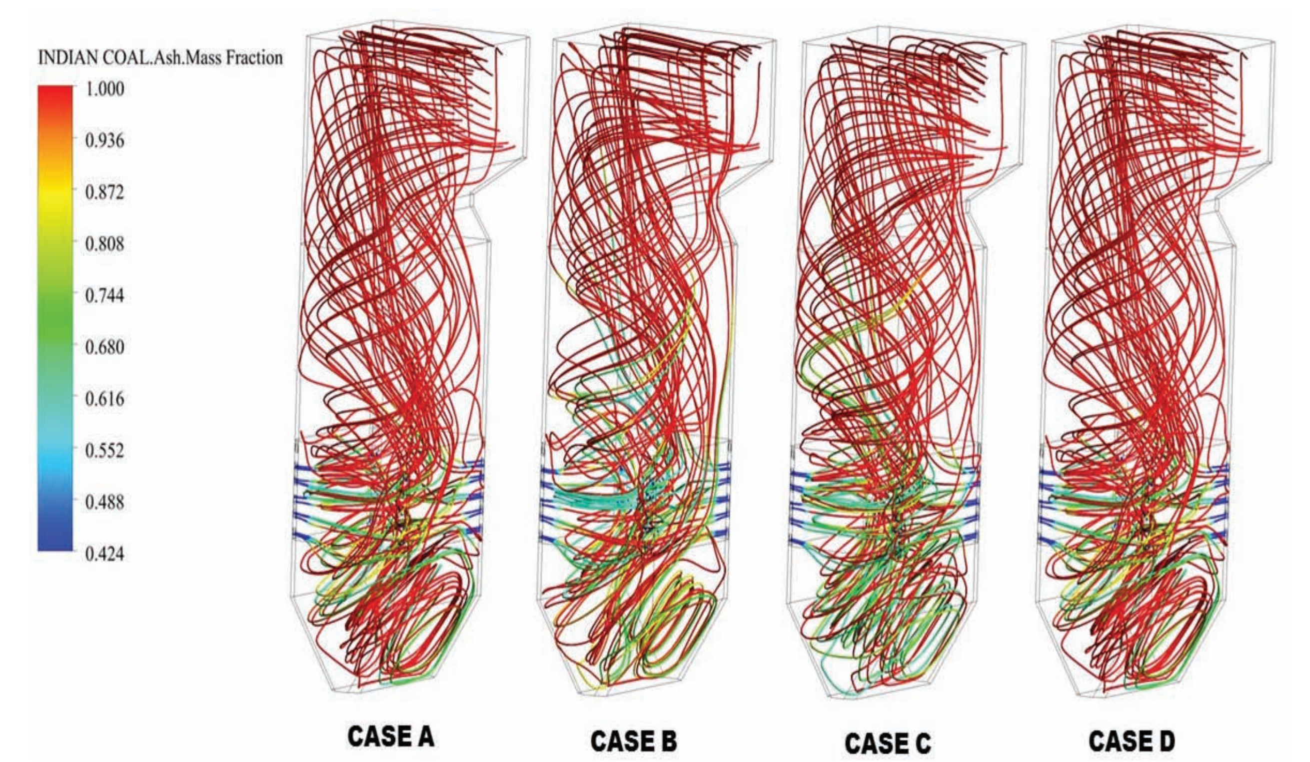

FIG. 5. PARTICLE ASH MASS FRACTION

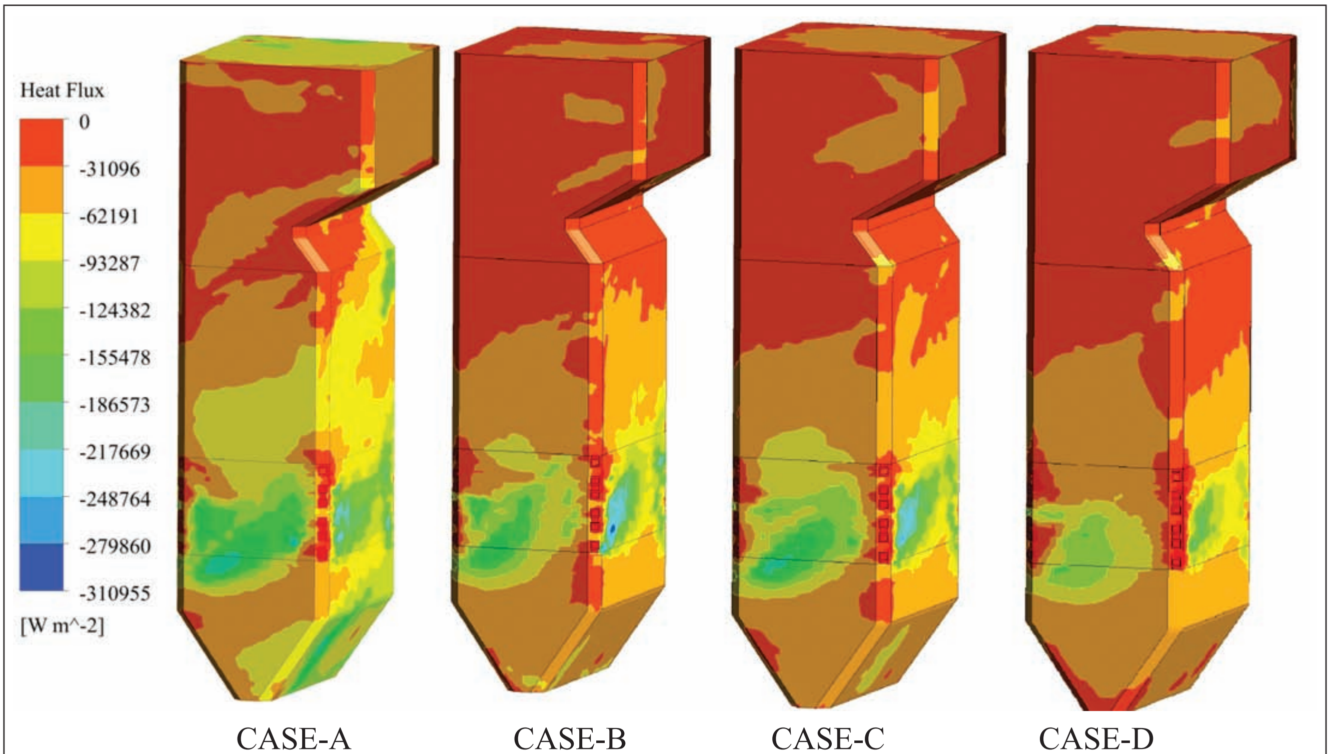

FIG. 6. WALL HEAT FLUX AT RIGHT AND REAR WALLS

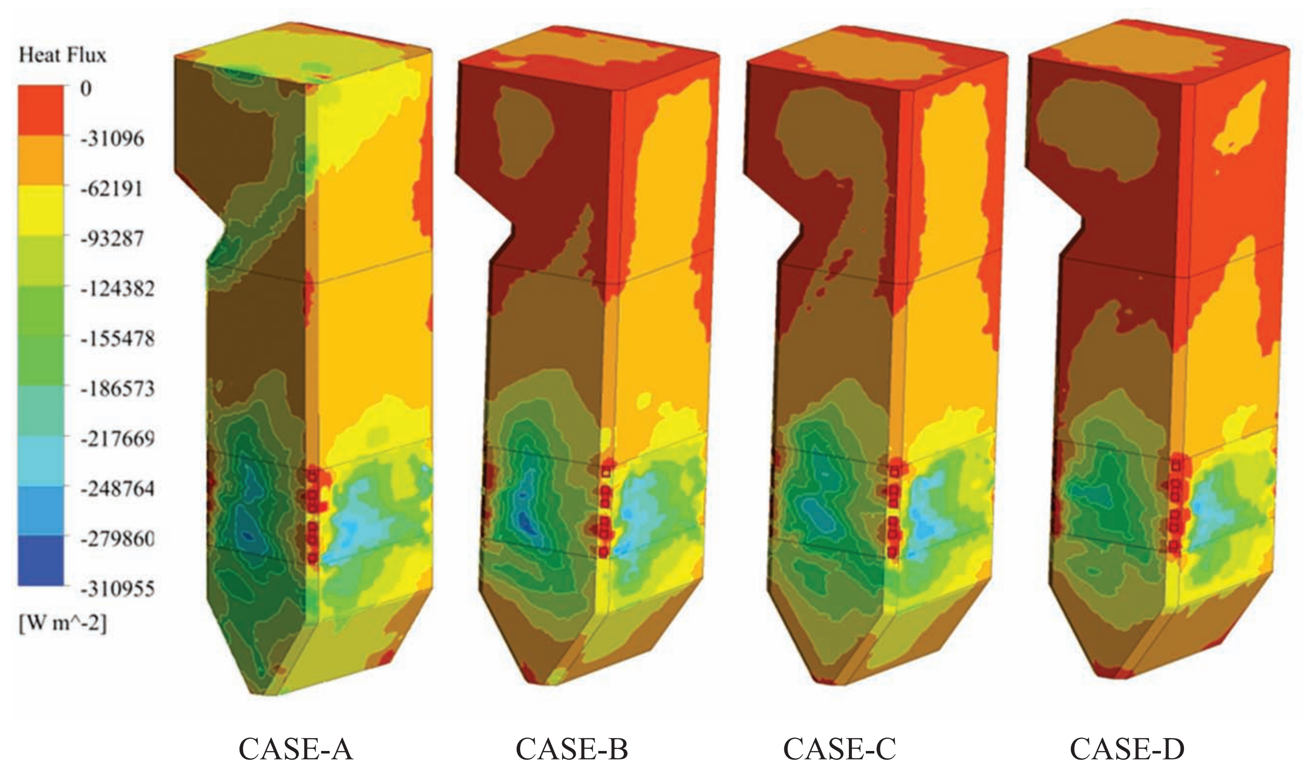

FIG. 7. WALL HEAT FLUX AT LEFT AND REAR WALLS

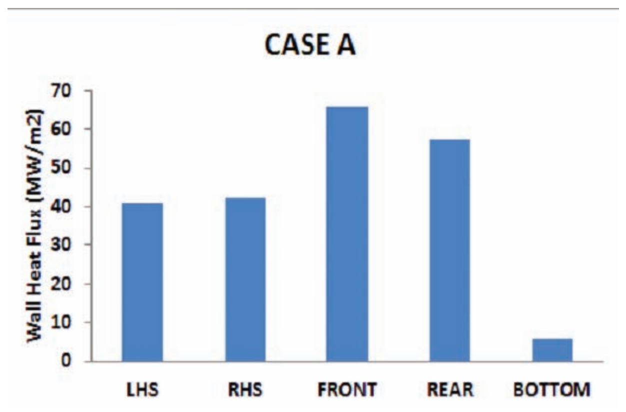

FIG. 8. HEAT FLUX DISTRIBUTION IN CASE A

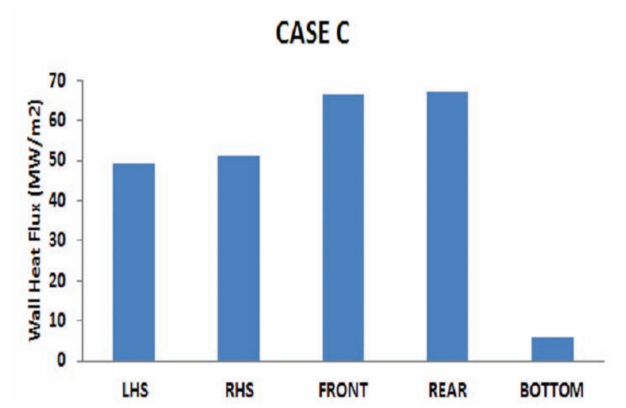

FIG. 10. HEAT FLUX DISTRIBUTION IN CASE C

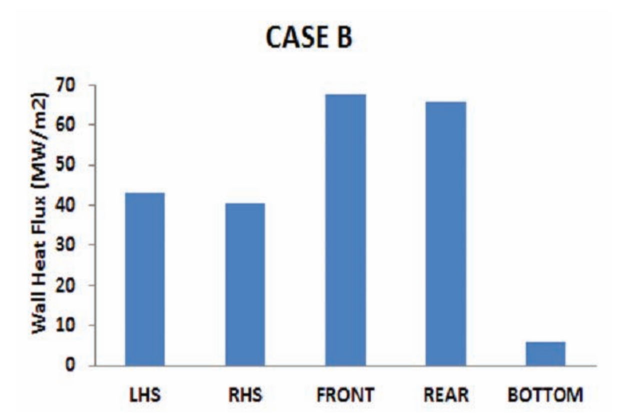

FIG. 9. HEAT FLUX DISTRIBUTION IN CASE B

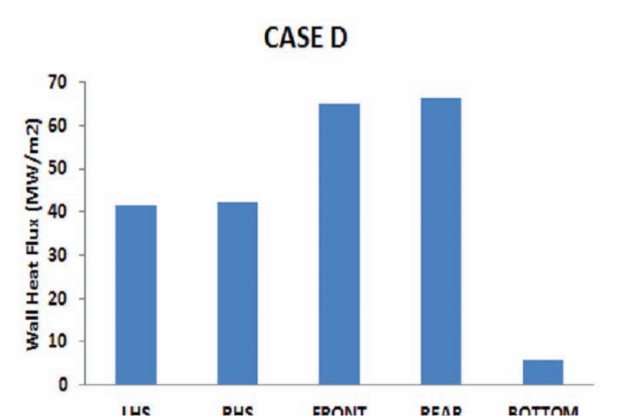

FIG. 11. HEAT FLUX DISTRIBUTION IN CASE D

5.0 CONCLUSIONS

The conclusions of the present study are given below:

1. The velocity profiles in all the four cases are found to be same as there was no significant variation in air input calculated for the four cases.
2. The combustion was complete in all the four cases as found from the ash profile of the particle track.
3. The heat flux distribution and the heat absorption profiles were found to be different in different walls as the flow in the boiler is not symmetric and the impact time for the flow is not same as the dimensions of the walls are different.
4. The total wall heat absorption was found more in the CASE C (80% Indian Coal and 20% Imported Coal) blend proportion compared to other blend proportions due to less ash input compared to other cases in which the heat energy required for the sensible heating of ash is less in the CASE C.
5. CFD is immensely helpful to understand the thermochemical reactions and the mass and energy transport occurring within the boiler during the blended coal combustion. The information obtained from the CFD results is useful in optimizing the combustion process to get better efficiency. The present paper indicates that the 80:20 combination is more thermally efficient than the pure Indian coal and also other combinations.

REFERENCES

[1] A Rushdi, A Sharma, and R Gupta, Fuel, Vol. 83, Issue 4-5, pp. 495-506, ISSN: 0016-2361, 2004.

[2] S Sua, J H Pohla, D Holcombeb, and J A Hartc, Techniques to determine Ignition, flame stability and burnout of blended coals in P.F. power station boilers, Progress in Energy and Combustion Science, Vol. 25, ISSN: 0360-1285, pp. 70–90, 1991.

[3] A M Carpenter, Coal blending for power stations, International Energy Agency (IEA) Coal Research/64 1993, ISBN 92-9029-225-3, pp. 5-100, 1995.

[4] WP Pan, Y G Mohamed, A Serageldin, A study of thermal analytical values for coal blends burned in an air atmosphere, Thermochimica Acta, Vol. 180, pp. 203-217, ISSN: 0040-6031, 1991.

[5] PCiambelli, International Conference on Technologies and Combustion for a Clean Environment, Lisbon, Vol. I, pp. 2-3, 1997.

[6] V Artos, W Alan , and Scaroni, T.G.A. and drop-tube reactor studies of the combustion of coal blends, Fuel, Vol. 72, pp. 927, ISSN: 0016-2361, 1993.

[7] J Qiu, F Li, H Zeng, B Yao, Y Ma. Determination of Optimum Blending Ratio During Coal Blends Combustion, Combustion Science and Technology, Vol. 157:1, pp. 167-184, ISSN: 0360-1285, 2000.

[8] S Sua, J H Pohl, D Holcombe, J A Hart, Techniques to determine ignition, flame stability and burnout of blended coals in p.f. power station boilers, Progress in Energy and Combustion Science, Vol. 27, pp. 75–98, ISSN: 0360-1285, 2001.

[9] T Beeley, C K Mana, J RGibbinsa, and JWilliamson, Development of TG measurements of intrinsic char combustion reactivity for industrial and research purposes, Fuel Processing Technology, Vol. 57, Issue 2, pp. 113–130, ISSN: 0378-3820, 1998.

[10] S Badzioch and P G W Hawksley, Ind. Eng. Chem. Process Des. Dev, Vol. 9, No 4, pp. 521 -532, ISSN 0196-4305, 1970.

[11] M A Field, Measurements of the effect of rank on combustion rates of pulverized coal, Combustion and Flame, Vol. 14, Issue 2, pp. 237-248, ISSN: 0010-2180, 1970.

[12] W Ranz and W R Marshall, Evaporation from Drops: Part I, Chemical Engineering Progress, Vol. 48, pp. 141, ISSN: 0360-7275, 1952.

[13] R Viskanta, M P Menguc, Radiation heat transfer in combustion systems, Progress Energy Combustion, Sci. 13, pp. 97–160, ISSN: 0360-1285, 1987.

[14] N G Shah; PhD thesis, Imperial College of Science and Technology, London, England, 1979.

[15] W E Ranz and W R Marshall; Chemical Engineering Progress, Vol. 48, pp. 101, ISSN: 0360-7275, 1955.

[16] L Schiller and A Naumann, VDI Zeits, 77, p 318-329, ISSN 1743-3533, 1933.

[17] B F Magnussen, The Eddy Dissipation Concept for Turbulent Combustion Modelling Its Physical and Practical Implications, International Flame Research Foundation, pp. 29, ISSN 2075-3071, 1989.

[18] L D Smoot & J P Smith, Coal Combustion and Gasification, The Plenum Chemical Engineering Series, Plenum Press New York. ISSN 0081-9573, 1985.

[19] J GIBB, Chemical Process Modelling of Underground Coal Gasification and Evaluation of Produced Gas Quality for End Use, Energy Procedia, Vol 76, pp 444-453, ISSN: 1876-6102, 2000.