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Research Article

Emissions Reduction by Combustion Modeling in the Riser of Fluidized Bed Combustor for Thar Coal Pakistan

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Abstract: Pakistan has experienced a protracted electricity shortage for the past few years. However, despite Pakistan's abundant coal deposits, modern coal combustion technology is still required to reduce emissions. Pakistan is struggling to utilize its energy resources and currently experiencing an electrical shortage of more than 8000 MW. The research study models the combustion performance in a fluidized bed riser using ANSYS FLUENT software to understand the combustion behavior of low-rank Thar coal. A simple circulating fluidized bed (CFB) combustion riser was modeled for computational fluid dynamics (CFD) to study the hydrodynamics of gas-solid flow in a circulating fluidized bed riser to reduce emissions and operating costs. Three different types of risers/combustors geometries were used center flow, counter flow, and parallel flow. The CFD model for the solids segment with a k-e turbulence model and the viscosity of static particles in the gas segment both showed excellent mixing performance. According to the FLUENT data, the riser/combustor maximum temperature is around 1400 K or 1130 ^{o}C at the primary burning sector in the bed center. According to velocity contours, the greatest velocity in the center-oriented riser/combustor peaks at 3.3 m/s. The CO and CO_2 both mass fraction counters show maximum concentration in the center geometry, whereas lower CO concentration is found in parallel geometry. The lowest level of NO_x is established in the parallel geometry at around 15 ppm, whereas the counter contours establish the maximum level of NO_x at about 31 ppm. Circulating Fluidized Bed Combustor is found to be the most advantageous and effective technology for producing power from Thar lignite coal and reducing emissions.

Keywords: Two-phase gas-solid flow model, Thar coal, Circulating fluidized bed, Hydrodynamic, Computational fluid dynamics, Riser, Emissions reduction

1. INTRODUCTION

Energy is widely acknowledged as one of the most crucial components of societal well-being and a prerequisite for long-term development. A consistent energy resource and demand are essential components for every government when it comes to offering consumers energy that is economical, ecological, and clean [1]. Over a third of the world's electricity is still produced by coal, the most widely produced mineral on earth [2]. About 37 % of the electricity produced globally was from thermal coal. Coal has continued to be a significant energy source for many years, especially while emission reduction technologies are gradually implemented [3]. According to International Energy Agency (IEA) in the coal forecast for 2021, all-time-high production of 8,111 Mt occurs in 2022.

Pakistan has enormous energy needs, and because of this, the constituency is most concerned about power outages lasting a long period [4]. For many years, Pakistan's main source of energy has been imported fossil fuels. Over 185 billion tons of coal are in Pakistan's reserves, although only 175.5 billion tons are from Thar coal [5, 6]. In the industrialized region, a significant number of oil and gas plants have been replaced by coal-fired power plants. Exploiting natural resources, such as

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the Thar coalfield, which can produce 100,000 MW, could be a practical solution to fulfill the predicted demand [7]. Coal still serves as a source of energy generation in Pakistan, where its share of the country's energy mix is 12.8 % [5]. Pakistan needs to understand the most recent coal technologies because of its vast coal deposits [8]. Coal's adverse environmental consequences are caused by the emissions of several pollutants such as SO_X, NO_X, CO, and CO_2 [9]. The current coal consumption makes it difficult to reduce air pollution from coal power plants. It is essential to create a system or tools to control these harmful coal emissions [10].

Combustion is a multifaceted procedure containing sequential heterogeneous and homogeneous reactions of a fuel with an oxidizer. The important combustion stages contain, heating and drying, devolatilization and volatile combustion, and char burning. In recent years, CFBCs are extensively used for power generation, because of their superior burning efficiency and relatively better control of emission gases [11, 12]. Fluidized bed combustion technology is being used more often around the world, which has prompted researchers to improve the design and lower emissions through additional tests and modeling [13, 14]. Surface reaction kinetics and diffusional mass transference work together in the complex coal-burning process. Due to the variety of configurations and their multiple effects on the solid-gas two-phase flow, there has been minimal research on the intake and outlet effects on the hydrodynamics in risers or combustors, but no precise classification or understanding has been reached.

Therefore, it is crucial to comprehend the riser inlet sections' hydrodynamic properties [15]. It has been demonstrated that a CFB's riser output geometry significantly affects the hydrodynamics of the component. Knowing the effects of various variables and factors on emission actions is crucial for effective emission management, particularly to reduce emissions of inadequate burning products [16-18]. With a production capacity of 175 billion tons, Thar lignite coal requires special consideration when integrating with modern technologies. Generally speaking, conventional boilers devalue coal and produce high NO_x levels. Therefore, CFBC technology has been developed and is used by modern enterprises and power locations due to reduced environmental risks and higher energy production efficiency [19]. A reduction in combustion emissions increased fuel investment, and higher combustion efficacy is all necessary for improving a combustion structure. Coal is an abundant fuel resource that can be used to produce and transform it into affordable energy. However, producing and using coal has an impact on the environment [20].

ANSYS FLUENT software comprises an extensive variety of physical modeling abilities that are used for turbulence, model flow, heat transfer, and reaction for engineering applications. Modeling with ANSYS code will reduce investment and working costs also simulation tool can solve multiple models in a single file which ultimately reduces the simulation time by three phases, pre-processing, solver, and post-processing [21]. Numerous studies have been published about CFD modeling of coal combustion in the CFB riser. Peters *et al.* [22] reported that the CFD codes deliver a shortcut to contract the comprehensive info in CFB risers for gas-solid flow. Hussain *et al.* [23] investigated that voidage beside the riser elevation is disturbed by the geometry of the CFB riser. The burning performance of low-ranking coal from Duki and Chamalung Baluchistan was used in a CFB Combustor. They found that increase in temperature has produced a rise in the volume of discharge gasses.

Considering all the above facts and challenges, current research is focused on mechanisms or modeling that especially reduce emissions. A simple CFB Combustion Riser was modeled using ANSYS Fluent software for the computational fluid dynamics (CFD) combustion analysis of Thar coal reserves. To reduce investment and operational costs, as well as emissions gases, this study analyzed the burning performance of low-grade Pakistani coals from Thar in a CFB riser. Before we obtain actual performance data from the future power plant in Pakistan useful to reduce power or electricity shortage, local coal is carefully analyzed.

2. MATERIALS AND METHODS

Thar coal used in this investigation was obtained from Thar Block-II. Eighty (80) samples n duplicates were chosen for evaluation in the current investigation. The results are a mean value of eighty representative samples taken from Pakistan's Thar Block-II coalfield. Physicochemical characteristics are analyzed for all coal samples as per ANSYS software requirements. Data collection was done using ASTM standard procedures such as Proximate Analysis (D-3172-5) and Ultimate Analysis ASTM (D-3176, D-5373). For physicochemical analysis, a Memmert oven and a Vulcan muffle furnace were used to perform a Proximate Analysis to determine the amounts of moisture, volatile, fixed carbon, and ash. Ultimate Analysis was performed with an Elementar CHNS analyzer to examine the H, C, S, and N components in the samples of coal.

Circulating Fluidized Bed Combustion (CFB) principle is the foundation of the combustion system, which uses coal as a fuel. A wide range of material modeling capabilities is included in ANSYS software 19.0, which is used in industry to model turbulence, response, heat transfer, and flow.

2.1 CFB Simulation

The CFB simulation diagrams are shown in (Figure 1). It consists of a primary and secondary cyclone, an airstream blower, a solid intake system, a stainless-steel supply, and a quick Plexiglas column. On a riser with quadrilateral dimensions of 2649 mm in height, 72 mm in depth, and 265 mm in width, the 2D simulation work was performed. The 2D design was chosen because it required the least amount of processing work and was sympathetic to the flowing outlines in risers with different exit geometry [17]. The operative limitations were chosen since they had been proven effective in large CFBCs. Fluent Inc. developed and owns the CFD reference tool FLUENT, which created a simulation. Sand components, air, and solid-gas components were used in that order. Table 1 summarizes the constraints used in the simulation model.

2.2 Boundary Conditions

All volume fractions and speeds of related segments are fixed at the intake. As a result of the uncondensed gas segment potential, the pressure at the intake is uncertain. The primary gas velocity and solid segment are being measured, as seen in

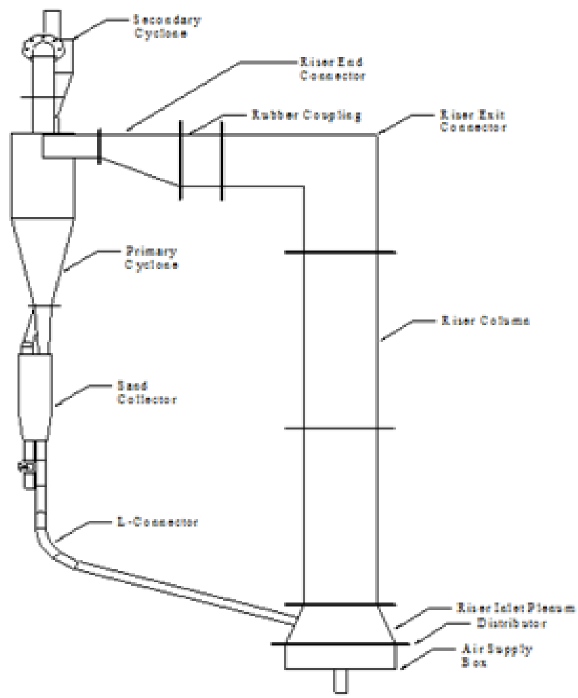


Fig. 1. Typical CFB riser geometry [17]

Table 1. The variables used in simulation work

Constraint	Values Range
Dimensions of Riser (LXWXD) mm	2649 X 265 X 72
Velocity (Particle)	2 m/s
Velocity (Gas)	3~5 m/s
Particle (sand) properties	Density = 2500 kg m^{-3} Diameter= 100X 10^{-6} m
Air Properties	Density= 1.225 kg m^{-3} Viscosity= 1.79 x 10^{-5} kg/m.s
Height of the distributor's sand intake	200 mm
Granular properties	0.95 is the coefficient of particle-particle restitution. Restitution coefficient for particle walls of 0.9
The fraction of sand by volume	Within 10% of the volume percentage of sand, 0.03 utilized as the Algebraic Slip Mixture Model provides reliable predictions.
Multiphase model	Eulerian granular multiphase model

(Table 2). The meshing process was completed using ANSYS FLUENT. Fine meshing was carried out in the direction of the riser in and out segments to analyze them in an improved fashion. Aspects were changed to achieve confluence below relaxation. The tolerance for confluence was set at 0.001.

The models used in ANSYS FLUENT to simulate the combustion of solid fuel are displayed in (Table 2).

Table 2. ANSYS FLUENT simulated models used

Model	Settings
Space	2D
Viscous	k-epsilon standard turbulence model
Time	Steady
Wall Treatment	Standard Wall Functions
Radiation model	P1 Model
Heat Transfer	Enabled
Species Transport	Generalized Finite Rate
Reactions Model	Eddy Dissipation
NO_X Model	Thermal & Prompt

2.3 Geometries of the Riser/Combustors

For the geometries of the risers/combustors, we have to consider the three different types according to their respective geometries. First, there is the center flow, counter flow, and parallel flow as shown in (Figure 2).

The grids are created using tri elements with an interval count of 10. An unstructured non-uniform triangle grid/mesh was used, due to the non-premixed combustion model, gas-solid being randomly spaced and do not follow any single pattern and having a strongly swirling flow inside the combustor/Riser shown in Figure 3. The iterations were calculated to an approximated time of 1 hour and 36 minutes. All the boundaries are also defined.

3. RESULTS AND DISCUSSION

The combustion characteristics of coal form the basis of the technology used for the power plant. The Thar Block-II coal assessment means data shows (Table 3) that moisture is high, volatile matter content is at low to medium levels, while sulfur and carbon are found low to moderate levels. The composition of the Thar Block-II coal is inputted as follows;

Table 3. Composition of Thar Block-II Coal

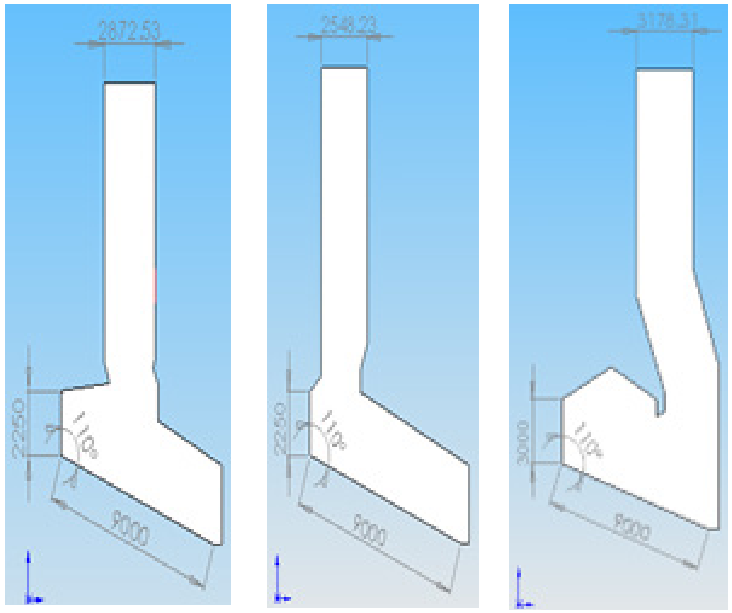
Proximate Analysis	Weight (%)
Moisture	46.26
Volatile Matter	28.85
Fixed Carbon	18.47
Ash	6.42
Ultimate analysis (DAF)	
Carbon	67.29
Hydrogen	4.30
Nitrogen	0.52
Oxygen	26.01
Sulfur	1.88

DAF= Dry Ash Free

Coal is burned using a variety of riser/combustors and combustion techniques. The main combustor is divided into three sections, primarily the burnout area, the combusting area, and the drying area. To start modeling gas flow, the properties of gaseous emittance and bed temperature are imported into the FLUENT program. The results demonstrate all of the combustion processes, including drying, devolatilization, char burning, and ash generation. The convergence of each simulation requires between 4,000 and 8,000 iterations.

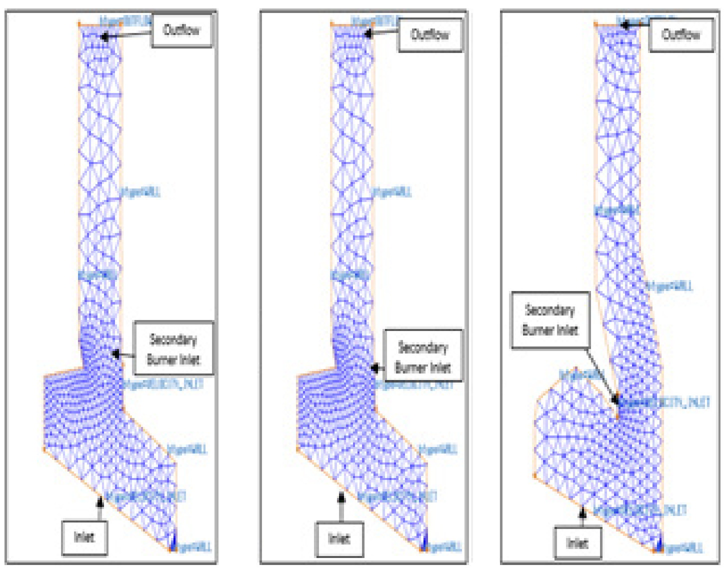
In (Figure 4) the static pressure contours in all three geometries calculate a maximum static pressure of 0.36 to 0.11 pascal and a minimum static pressure of -1.9 to -1.24 pascal. These statistics are small in comparison to atmospheric pressure; hence we can determine that the term strategy pressure in the compartment won't be caused any trouble.

The velocity contours (Figure 5 & Figure 6) show that the maximum velocity of the center-oriented riser/combustor is 3.3 m/s. We can see that as flue gases exit the primary chamber, all three velocities are at their maximum near the neck region. According to the velocity stream contours, the left-side wall at the neck area on the counter scenario may have issues due to fouling, slagging, and corrosion. In the third scenario, the right side of the neck wall may present us with a similar challenge. This is because the gas discharge stream



(a) Center Flow (b) Counter Flow (c) Parallel Flow

Fig. 2. Geometries of the Riser/Combustors (mm)



(a) Center Flow (b) Counter Flow (c) Parallel Flow

Fig. 3. Meshing of Coal Solid Fuel Combustor

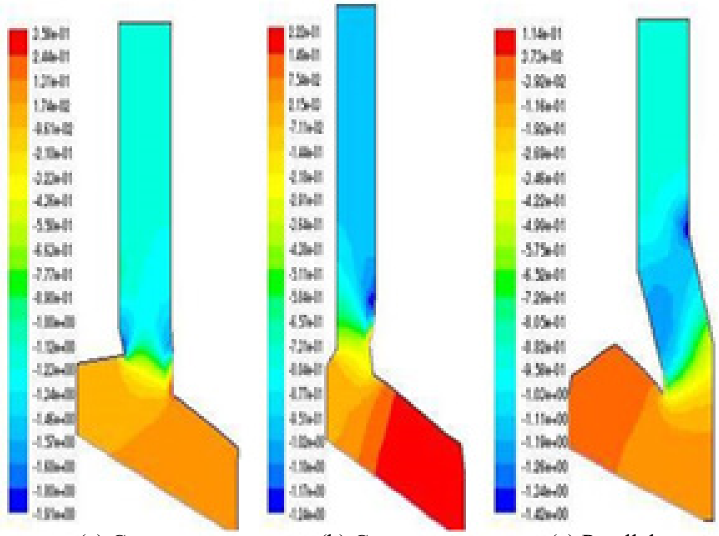
is concentrated close to the wall.

In (Figure 7) the central portion of the grate experiences the highest heat in all three scenarios, with the extreme temperature falling between 1400 K and 1440 K. Due to the high temperature in this area, volatiles is burned.

The burning of the volatiles is defined by two reactions:

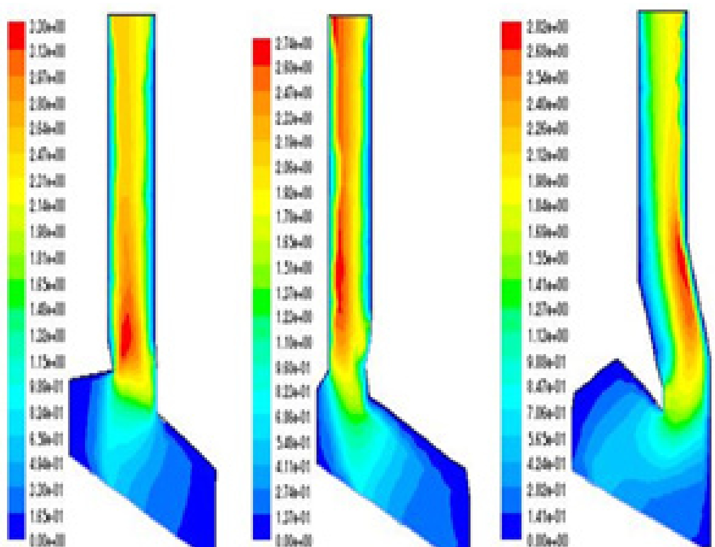
$2CO + O_2 \rightarrow 2CO_2$
$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$

The CO mass fraction contours (Figure 8) show that the central region of the grate, where devolatilization from the waste bed occurs, is where it is concentrated. Then, it is burned with oxygen to make CO_2. The center region contains both the lowest O_2 and greatest CO_2 concentrations (Fig. 9). We can observe (Figure 10) the lowering of O_2 at the secondary combustor area at the neck after CH_4 produced CO_2 and H_2O in response. The contours (Figure 11) indicating the amount of NO_x in ppm highlight the area of the geometry where it is frequently focused in the upper region. The lowest level is established by the parallel geometry



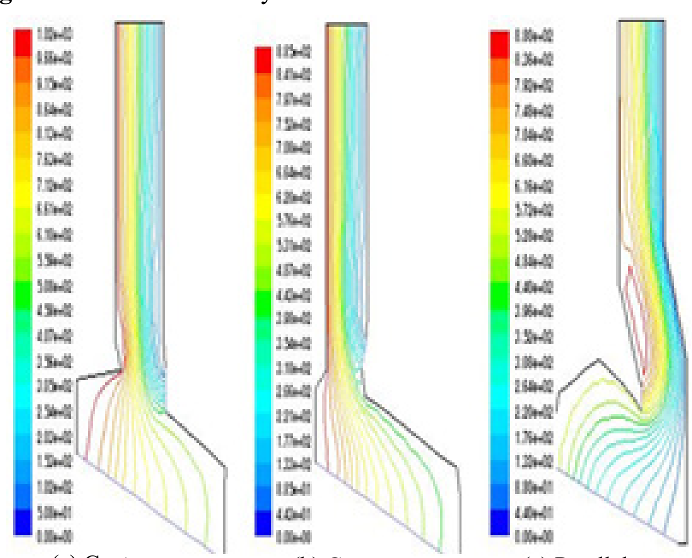
(a) Center (b) Counter (c) Parallel

Fig. 4. Contours of Static Pressure



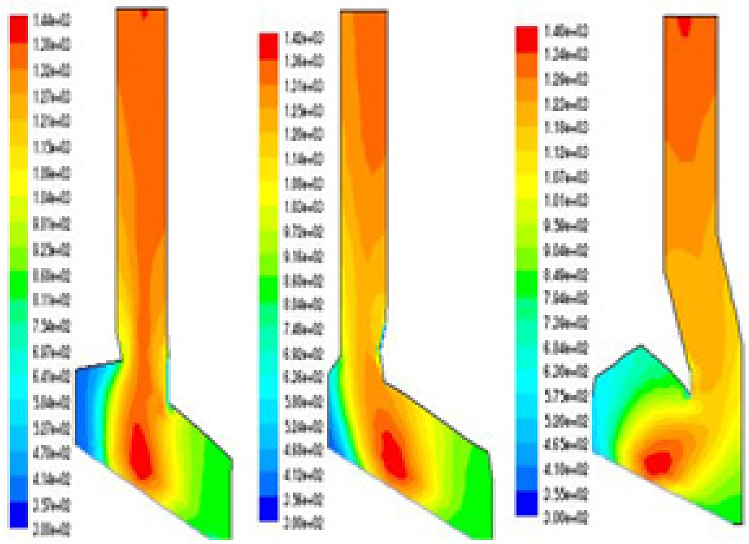
(a) Center (b) Counter (c) Parallel

Fig. 5. Contours of Velocity



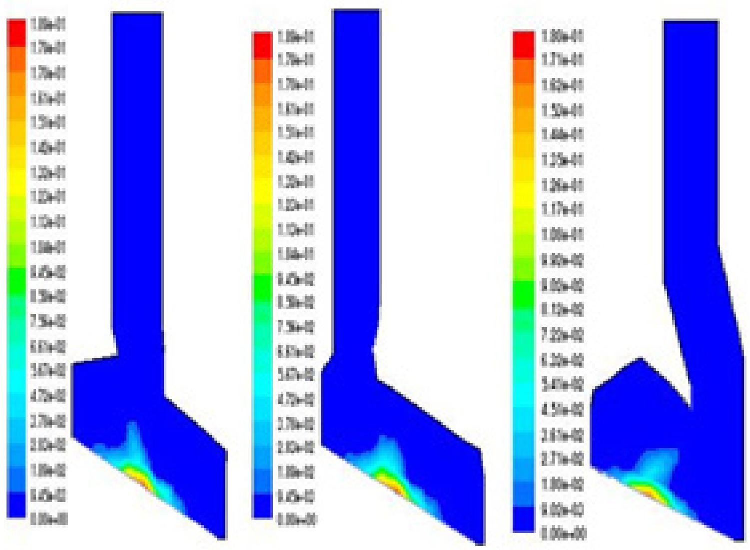
(a) Center (b) Counter (c) Parallel

Fig. 6. Contours of Velocity Stream



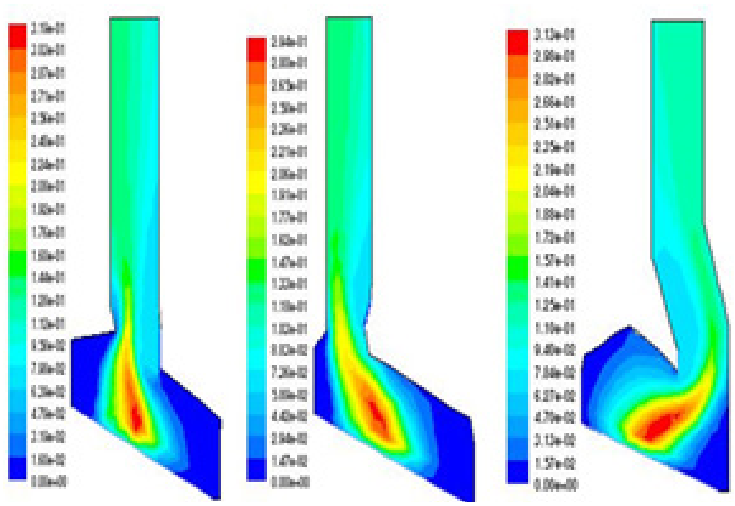
(a) Center (b) Counter (c) Parallel

Fig. 7. Contours of Static Temperature



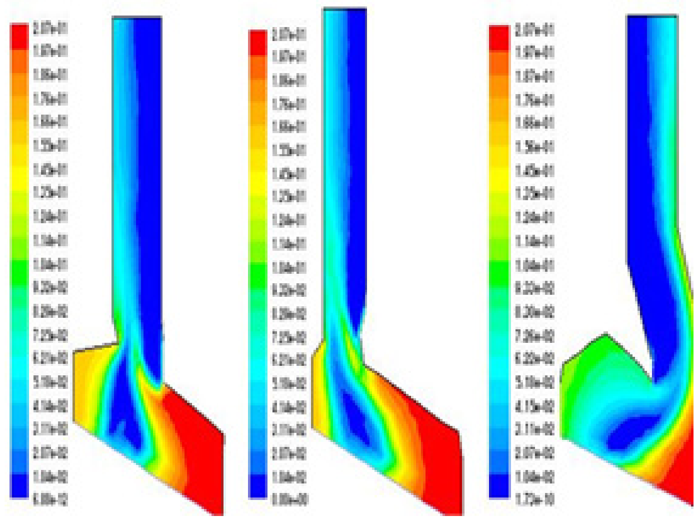
(a) Center (b) Counter (c) Parallel

Fig. 8. Contours of Mass Fraction of CO



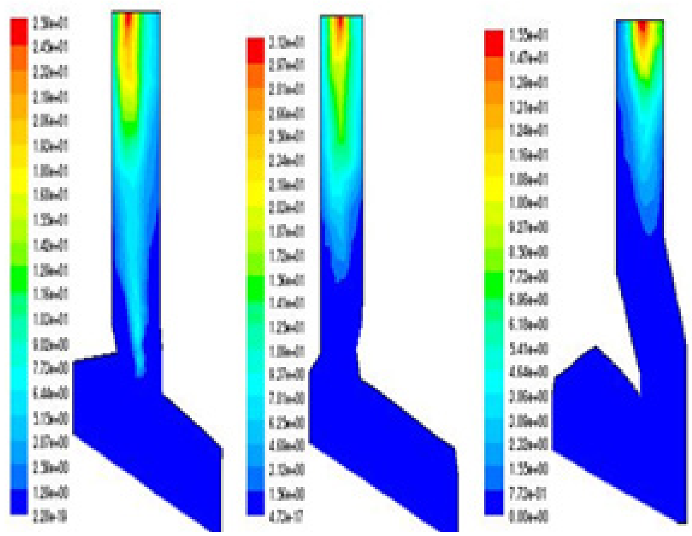
(a) Center (b) Counter (c) Parallel

Fig. 9. Contours of Mass Fraction of CO_2



(a) Center (b) Counter (c) Parallel

Fig. 10. Contours of Mass Fraction of O_2



(a) Center (b) Counter (c) Parallel

Fig. 11. Contours of NO_x (ppm)

at around 15 ppm, while the greatest level is established by the counter geometry at about 31 ppm.

4. CONCLUSION

A CFD model was developed to examine the hydrodynamics of gas-solid flow in a circulating fluidized bed riser using the commercial ANSYS FLUENT software. The parametric examination of the two-phase gas-solid stream hydrodynamics of a CFB riser was used to model the impact of various riser exit forms. For analyzing mixing performance, the CFD model for the gas segment and the viscosity of static particles in the solids segment with a k-ϵ turbulence model were used. The FLUENT data indicate that the highest temperature within the compartment is around 1400 K, or nearly 1130 °C, at the primary burning sector in the bed center. The highest velocity in the center-oriented riser/combustor peaks at 3.3 m/s, according to velocity contours. The CO and CO_2 mass fraction contours show that it is concentrated in the center geometry and lower CO concentration is found in parallel geometry. The lowest level of NO_x is established by the parallel geometry at around 15 ppm, while the greatest level is indicated by the counter contours at about 31 ppm. To reduce emissions, it is determined that the Circulating Fluidized Bed Combustor is the most advantageous and efficient technique for producing power from Thar lignite coal. However, to validate the results of

CFD modeling, further studies may be conducted and actual data from a current fluidized combustor may be used.

5. ACKNOWLEDGMENTS

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6. CONFLICT OF INTEREST

There is no conflict of interest among the researchers of this study.

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