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Numerical Study of the Effects of the Primary Air/Secondary Air Ratio and Coal Quality on Combustion Characteristics and Emissions in a 115 MW CFB Power Plant

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CFD; Boiler CFB; PA/SA Ratio; LRC; MRC; Emisi NOx.

Abstract
The distribution of combustion air in a Circulating Fluidized Bed (CFB) boiler plays an important role in determining combustion performance and emission formation. Variations in coal quality result in differences in combustion characteristics, making it necessary to optimize the Primary Air/Secondary Air (PA/SA) ratio. This study aimed to analyze the effects of PA/SA ratio variations and coal quality on temperature distribution and exhaust gas composition in a 115 MW CFB power plant. The simulation was conducted using Computational Fluid Dynamics (CFD) with Ansys Fluent 2024 R2 software, incorporating PA/SA ratio variations of 40/60, 50/50, 60/40, and 70/30 for two coal types: Low-Rank Coal (LRC) and Medium-Rank Coal (MRC). The analyzed parameters included temperature distribution and mass fractions of CO_2, O_2, and NOx. The simulation results showed that PA/SA ratios of 40/60 and 50/50 produced more homogeneous temperature distributions compared with the 60/40 and 70/30 ratios. MRC produced higher furnace temperatures than LRC but also resulted in increased NOx emissions. The highest CO_2 mass fractions were obtained at PA/SA ratios of 40/60 and 50/50, with values of approximately 0.16–0.17, indicating more effective carbon conversion. An increase in the primary air ratio increased the concentrations of O_2 and NOx in the furnace. Overall, the 50/50 PA/SA ratio provided the optimal combustion performance, characterized by a more homogeneous temperature distribution, high carbon conversion efficiency, and controlled NOx emissions.

INTRODUCTION

A Circulating Fluidized Bed (CFB) boiler is a coal combustion technology widely used in power plants due to its high fuel flexibility, good combustion efficiency, and relatively lower emissions compared with conventional combustion technologies (Basu, 2015). In CFB boilers, the distribution of combustion air between primary air (PA) and secondary air (SA) is a critical operating parameter because it influences particle fluidization, temperature distribution, combustion efficiency, and exhaust gas emission formation (Gonzales et al., 2024; J. Xu et al., 2025; S. Xu et al., 2022; Zheng et al., 2019).

Primary air functions to fluidize the bed material and transport fuel particles, whereas secondary air is injected at specific elevations to enhance combustion through a staged combustion mechanism. According to Basu (2015), staged combustion can improve temperature uniformity while reducing nitrogen oxide (NOx) formation by creating a reducing zone in the lower furnace region. Lee et al. (2013) demonstrated that variations in the PA/SA ratio significantly affect furnace temperature and CFB boiler performance, while Yan et al. (2019) reported that secondary air distribution influences exhaust gas composition throughout the furnace. Furthermore, H. Liu et al. (2023) showed that increasing secondary air can reduce NOx emissions through enhanced staged combustion mechanisms.

In addition to air distribution, coal quality also affects combustion characteristics. Variations in moisture content, calorific value, and volatile matter content result in differences in temperature distribution and emission formation during combustion (Mataufani et al., 2023; Sa'adiyah et al., 2017). However, studies comparing the effects of PA/SA ratio variations on different coal qualities, particularly Low-Rank Coal (LRC) and Medium-Rank Coal (MRC), in utility-scale CFB boilers remain limited (Li et al., 2018b, 2018a; Wu et al., 2026).

The urgency of this research is driven by the need for power plants to maintain efficient and environmentally sustainable operations while managing variations in coal quality. With increasing efforts to reduce greenhouse gas emissions and comply with stricter environmental regulations, optimization of combustion parameters has become increasingly important. The findings of this study may provide valuable insights for plant operators in determining appropriate PA/SA ratios according to coal characteristics, thereby improving combustion efficiency and reducing emissions. This is particularly relevant for coal-dependent power plants in Indonesia and other developing countries (Canpolat et al., 2026; Do & Burke, 2024; Dzikrurrokhim et al., 2026; Kural & Rosalia, 2026; Sujai et al., 2023).

The novelty of this research lies in its systematic evaluation of the combined effects of PA/SA ratio variations and coal quality in a utility-scale CFB boiler. Specifically, this study employed a comprehensive CFD approach to analyze four PA/SA ratio configurations (40/60, 50/50, 60/40, and 70/30) for two coal types (LRC and MRC) in a 115 MW CFB boiler. The application of full-scale boiler geometry, supported by validation using actual operational data, provided more representative results compared with laboratory-scale investigations. In addition, this study simultaneously evaluated temperature distribution and the mass fractions of CO_2, O_2, and NOx to provide a comprehensive assessment of combustion performance (Al-qazzaz et al., 2024; Emami et al., 2019; Panahi et al., 2019; Shaker et al., 2023; Si et al., 2021).

Therefore, this study aimed to analyze the effects of PA/SA ratio variations and coal quality on temperature distribution and CO_2, O_2, and NOx exhaust gas distributions in a 115 MW CFB boiler using a Computational Fluid Dynamics (CFD) approach. The results were expected to provide a basis for determining an optimal PA/SA ratio to achieve improved combustion performance and lower emissions (Deng et al., 2020; Kim et al., 2025; Kirch et al., 2018; Sanchez-Polito et al., 2024; Zadravec et al., 2021).

METHOD

Geometry and Operating Conditions

The study object was a 115 MW Circulating Fluidized Bed (CFB) boiler operated at 75% Maximum Continuous Rating (MCR). A three-dimensional boiler model was developed based on the actual geometry (Figure 1) and simulated using Ansys Fluent 2024 R2 software. The simulation employed the Eulerian multiphase approach to model gas–solid interactions in the CFB boiler. The energy equation was activated to predict temperature distribution within the furnace, while the standard k–ε turbulence model was applied to simulate turbulent flow during the combustion process (Wijayanto et al., 2018).

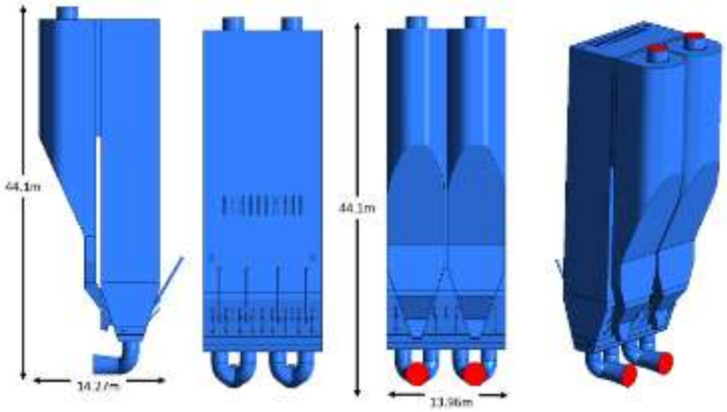

Figure 1. Boiler Geometry

Radiant heat transfer was modeled using the Discrete Ordinates (DO) radiation model, which was suitable for high-temperature participating media and complex three-dimensional geometries. The combustion process and gas species distribution were modeled using the Species Transport Model, while coal particle injection and movement were simulated using the Discrete Phase Model (DPM).

Nitrogen oxide (NOx) emissions were predicted using the Fuel-NOx mechanism. The Thermal-NOx and Prompt-NOx mechanisms were neglected because the operating temperature of CFB boilers typically ranges from 800–950°C, which is below the temperature range where significant Thermal-NOx formation generally occurs. Therefore, NOx formation was assumed to be primarily influenced by the conversion of nitrogen contained in the fuel.

The combustion process was modeled using a two-step volatile combustion mechanism consisting of volatile matter oxidation to CO and subsequent CO oxidation to CO_2. In addition, char oxidation, Boudouard, water-gas, and hydrogen combustion reactions were incorporated to represent the combustion and gasification processes occurring in CFB boilers. The reaction equations were adjusted according to the ultimate analysis characteristics of each coal type, namely Low-Rank Coal (LRC) and Medium-Rank Coal (MRC). The computational domains used in the simulation are presented in Figure 2.

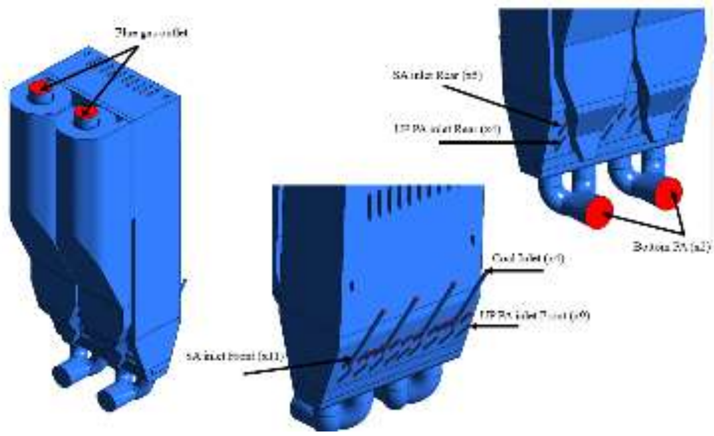

Figure 2. Modeling Limit Conditions

Grid Independency Test

The grid independence test was carried out using three mesh variations, namely 1,257,858, 2,172,722, and 5,849,030 elements. The results of the meshing can be seen in Figure 3, and the results of the grid independence test can be seen in Figure 4. The yield difference between medium and fine mesh is only 0.48% for speed and 0.002% for temperature. Therefore, a mesh with 2,172,722 elements was chosen because it has met the criteria of grid independence with better computing efficiency.

Figure 1 Meshing

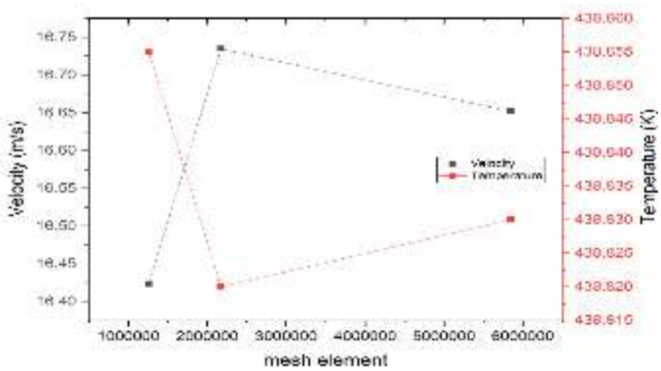

Figure 2 Temperature and velocity distribution for each mesh

Simulation Variations

The simulation was carried out using two types of coal, namely:

1. Low Rank Coal (LRC)
2. Medium Rank Coal (MRC)

Table 1 Data Analysis of coal proximate and ultimate

	Proximate Analysis			Ultimate Anlysis		
	Material	Unit	As Received (AR)	Material	Unit	Dry Ash Free (DAF)
MRC	Volatile	%wt	30.94	Carbon	%wt	62
	Fixed carbon	%wt	34.96	Hydrogen	%wt	6.1
	Ash	%wt	4.49	Oxygen	%wt	30.1
	Total Moisture	%wt	29.61	Nitrogen	%wt	1.15
				Sulphur	%wt	0.82
LRC	Volatile	%wt	28.52	Carbon	%wt	52
	Fixed carbon	%wt	27.9	Hydrogen	%wt	5.5
	Ash	%wt	3.12	Oxygen	%wt	41.3
	Total Moisture	%wt	40.46	Nitrogen	%wt	0.95
				Sulphur	%wt	0.29

The variations in the combustion air ratio used are:

Table 2 Variations used in simulations

Variasi	BB Quality	Total Flow BB	PA/SA Ratio	PA		SA
				UP PA	Bottom PA	
		kg/s		kg/s	kg/s	kg/s
Case 1	LRC	16.62	40/60	7.28	41.24	72.78
Case 2			50/50	9.1	51.55	60.65
Case 3			60/40	10.92	61.86	48.52
Case 4			70/30	12.74	72.17	36.39
Case 5	MRC	13.21	40/60	7.52	42.65	75.27
Case 6			50/50	9.4	53.31	62.73
Case 7			60/40	11.2	63.98	50.18
Case 8			70/30	13.17	74.64	37.64

So that eight simulation scenarios were obtained which are a combination of variations in the PA/SA ratio and coal quality.

Model Validation

The CFD model is validated using actual temperature data on furnaces, cyclones, and boiler outlets. The validation results showed an average error of 5.08%, which is still below the tolerance limit of 10%, so the model is considered to be able to represent boiler operating conditions well.

Table 3 Simulation temperature data and field data

OVERVIEW POINT	FIELD DATA	SIMULATION	ERROR	ERROR
	(°C)	(°C)		(%)
FURNACE	894	944.58	50.58	5.66
CYCLONE	768.83	787.71	18.88	2.46
OUTLET	729	781	52	7.13

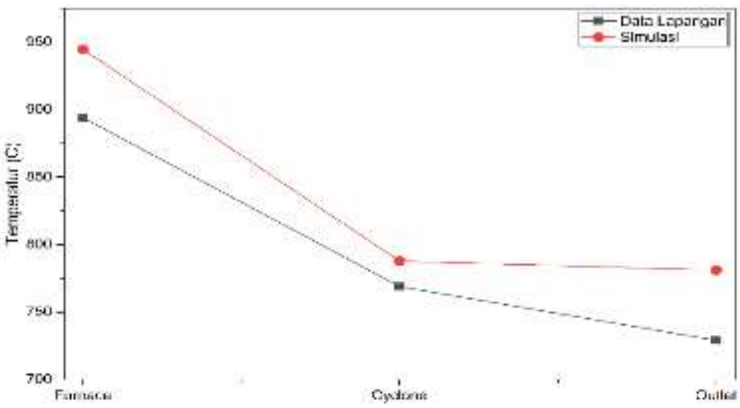

Figure 3 Temperature Graph Based on Field Data and Simulation Results

Analysis Parameters

The analyzed parameters include:

1. Distribusi temperatur furnace.
2. Mass fraction distribution of CO_2.

3. Mass fraction distribution O_2.
4. Mass fraction distribution of NOx.

The analysis is carried out through the evaluation of the distribution contour and parameter profile of the furnace height.

RESULTS AND DISCUSSION

Temperature Distribution

The temperature distribution shows that the PA/SA ratio has a significant influence on combustion homogeneity. In both types of coal, the PA/SA ratios of 40/60 and 50/50 result in a relatively even temperature distribution throughout the furnace volume. An increase in the proportion of secondary air increases the mixing between fuel and oxygen so that combustion takes place more homogeneously.

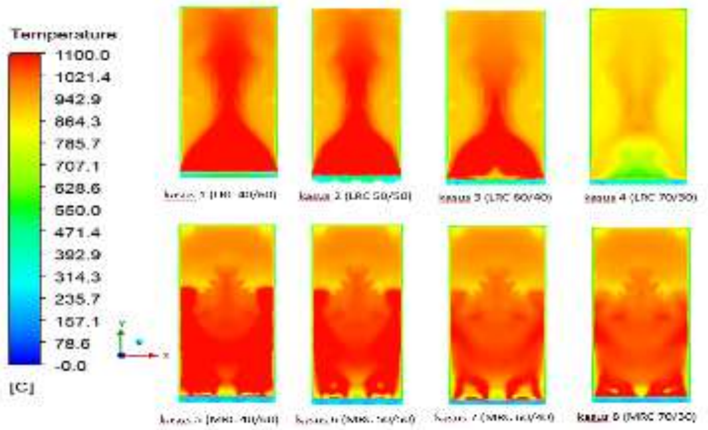

Figure 4 Temperature Contours On the Z-Axis Center Cross-Section of the Furnace

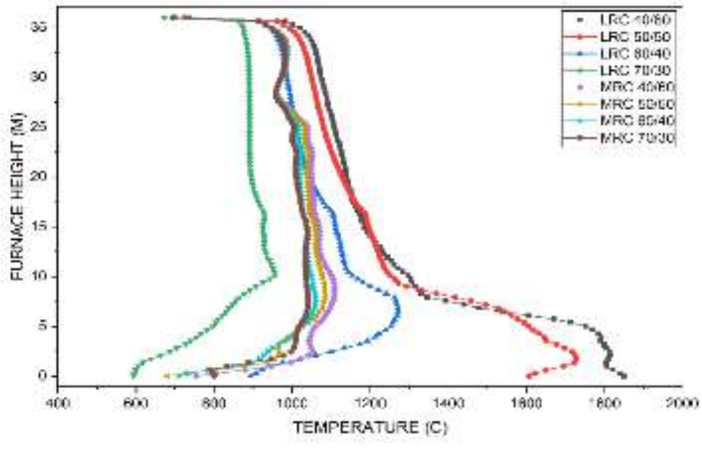

Figure 5 Plot of Temperature Against Furnace Height on the Furnace Centerline

On the other hand, in the 60/40 and 70/30 ratios, a more localized high temperature zone is formed in the center of the furnace. This condition indicates that the dominance of primary air causes the combustion process to be concentrated in the main flow path and decreases the homogeneity of heat distribution.

A comparison of coal quality shows that MRC produces higher and more stable temperatures than LRC across all PA/SA variations. This is related to higher calorific values and lower moisture content so that heat release takes place more intensively.

CO_2 Distribution

The CO_2 distribution is used as an indicator of the carbon conversion rate during the combustion process. The simulation results showed that the highest CO_2 mass fraction was obtained at the PA/SA ratio of 40/60 and 50/50 with a value of about 0.16–0.17. These conditions indicate that the carbon oxidation process takes place more perfectly than other variations.

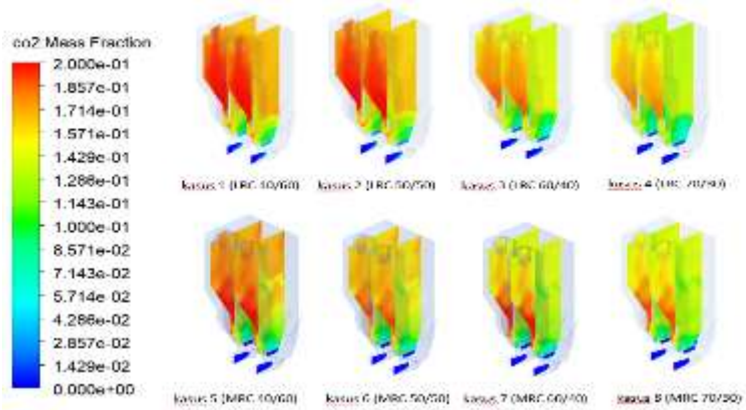

Figure 6 Contour of mass fraction at x-cross section for all casesCO_2

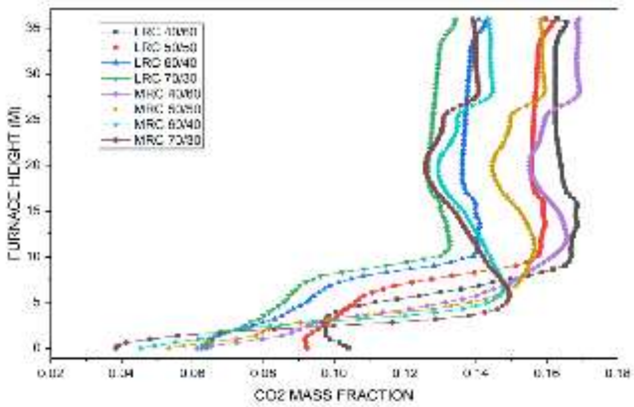

Figure 7 Plot of Mass Fraction to Furnace Height on the Furnace Centerline For Each CaseCO_2

At a PA/SA ratio of 70/30, the mass fraction of CO_2 tends to be lower due to a reduced proportion of secondary air that functions to improve combustion in the freeboard zone. This phenomenon suggests that excessive increase in primary air can decrease the effectiveness of carbon conversion.

O_2 Distribution

The residual O_2 concentration tends to increase with increasing proportion of primary air. This condition indicates that the utilization of oxygen becomes less effective due to the reduced contribution of secondary air in increasing the mixing of air and fuel. Similar phenomena have also been reported in CFB boilers (X. Liu et al., 2020), where changes in the PA/SA distribution affect the O_2 content in the exhaust gases and the level of excess water during the combustion process. This condition indicates that some oxygen is not utilized optimally due to the decrease in the effectiveness of air and fuel mixing.

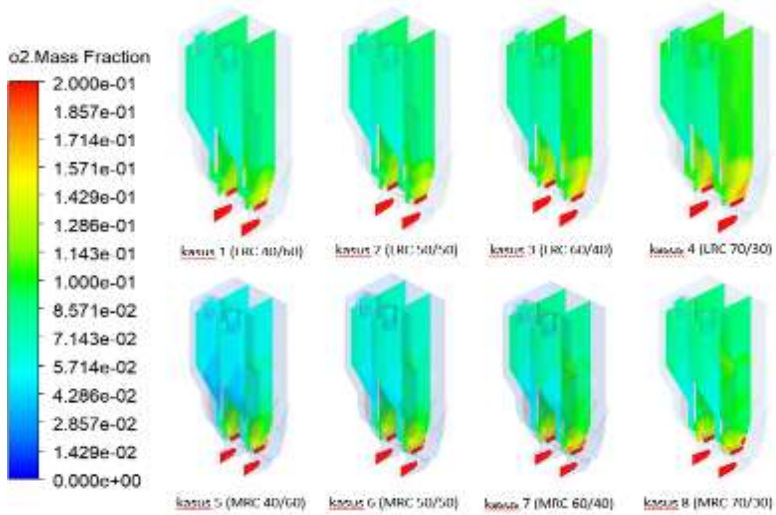

Figure 8 Contour of the mass fraction at x-cross section for all casesO_2

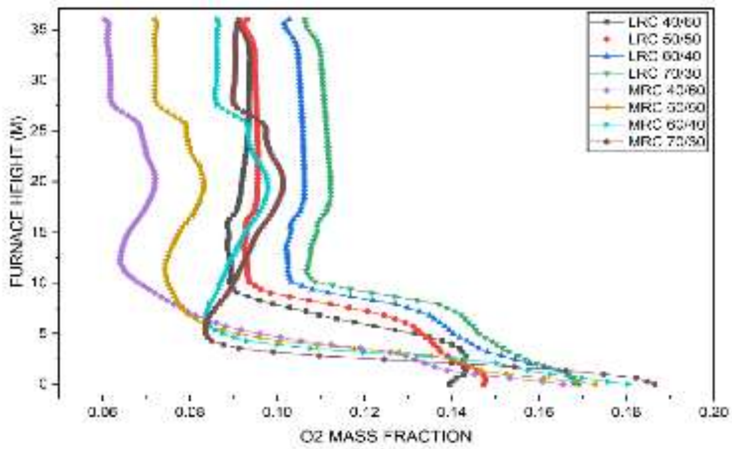

Figure 9 Plot of Mass Fraction of O2 to Furnace Height at the Furnace Centerline For Each Case

MRC coal produces a lower mass fraction of O_2 than LRC at the same PA/SA ratio. This shows that MRC combustion takes place more intensively so that oxygen consumption becomes greater.

NOx Distribution

The NOx distribution shows an increasing trend as the primary air ratio increases. The PA/SA ratio of 70/30 results in the highest NOx concentrations for both types of coal. This condition occurs due to a reduced proportion of secondary air that plays a role in maintaining the staged combustion mechanism.

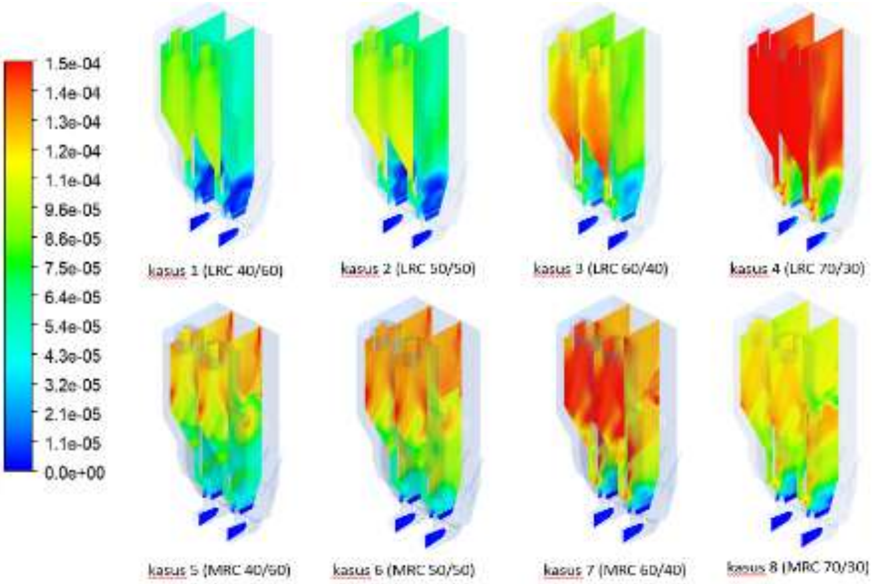

Figure 10 Contour of the mass fraction at x-cross section for all casesNOx

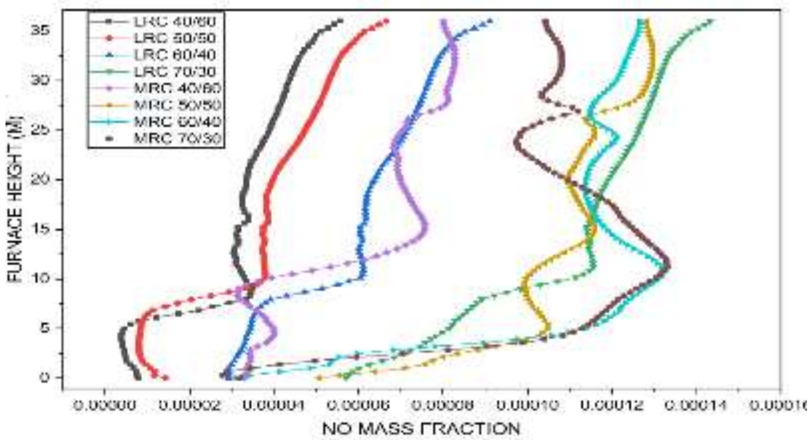

Figure 11 Plot of NOx mass fraction to Furnace Height at Furnace Centerline for each Case

At lower PA/SA ratios, secondary air forms a reduction zone at the bottom of the furnace so that some of the nitrogen compounds can be reduced to N_2 before being oxidized to NOx. These results are in line with research (Yan et al., 2019) and (H. Liu et al., 2023)which suggests that an increase in the proportion of secondary air can suppress the formation of NOx in CFB boilers.

MRC coal produces higher NOx emissions than LRC in all PA/SA variations. This is related to higher combustion temperatures thus accelerating the oxidation reaction of fuel nitrogen. Although thermal NOx is not the dominant mechanism in CFB boilers, the increase in temperature still accelerates the kinetics of the oxidation reaction of fuel nitrogen compounds into NOx (Tourunen et al., 2009)

Determination of the Optimum PA/SA Ratio

The determination of the optimum ratio is carried out based on four main parameters, namely temperature homogeneity, carbon conversion (CO_2), oxygen utilization (O_2), and NOx emissions. The PA/SA ratios of 40/60 and 50/50 show the best performance on most parameters. However, a 50/50 ratio provides a better balance between homogeneous temperature distribution, high carbon conversion, effective oxygen consumption, and controlled NOx emissions. Therefore, a PA/SA ratio of 50/50 was established as the most optimal operating condition in the 115 MW CFB boiler studied.

CONCLUSION

Variations in the PA/SA ratio and coal quality significantly influenced the combustion characteristics and exhaust gas distribution of the 115 MW CFB boiler. PA/SA ratios of 40/60 and 50/50 produced more homogeneous temperature distributions and higher CO_2 mass fractions compared with the 60/40 and 70/30 ratios. An increase in the primary air ratio increased O_2 and NOx concentrations due to the reduced effectiveness of staged combustion. MRC coal generated higher combustion temperatures than LRC but also resulted in higher NOx emissions. Based on the evaluated parameters, the 50/50 PA/SA ratio provided the best combustion performance by achieving a more homogeneous temperature distribution, higher carbon conversion, efficient oxygen utilization, and controlled NOx emissions.

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