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Research Article

Coal Switching-Induced Boiler Overheating Prevention through Integrated CFD Fireball Analysis and Coal Velocity Balancing

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Abstract: Coal switching to 100% Low-Rank Coal (LRC) in pulverized coal-fired power plants often induces combustion instability and increases the risk of localized superheater overheating due to uneven coal–air distribution. Differences in coal pipe velocities can lead to fireball displacement and non-uniform heat release inside the furnace. This study proposes an integrated preventive approach combining Computational Fluid Dynamics (CFD)-based fireball analysis and Coal Velocity Balancing (CVB) to improve combustion stability and mitigate overheating during full LRC operation. A full-scale case study was conducted at a 300 MW Rembang CFPP operating full-load LRC firing. CFD simulations were initially performed to identify fireball displacement and temperature non-uniformity. Based on the simulation results, mechanical orifice adjustments were applied to pulverizers A, B, and D to restore coal velocity uniformity across burner pipes. The combined numerical and field measurement results show a significant reduction in coal flow maldistribution, improved flame symmetry, and lower as well as more uniform outlet flue gas temperatures. These improvements indicate reduced thermal stress on critical boiler components, particularly the superheater. In addition, a slight reduction in coal consumption was achieved without compromising boiler load, indicating improved combustion efficiency. This study confirms that the integration of CFD-based fireball diagnostics and on-site coal velocity balancing provides a practical and cost-effective preventive strategy for mitigating boiler overheating during coal switching to low-rank fuel.

Keywords: Coal Switching; Low-Rank Coal; Coal Velocity Balancing; CFD Modeling; Combustion Optimization.

1. Introduction

The transition to alternative fuel sources, particularly low-rank coal (LRC), is a growing trend in thermal power generation due to economic and availability considerations [1]. However, LRC poses several combustion-related challenges such as high moisture content, lower calorific value, and greater propensity for uneven combustion distribution within the furnace [2]. These factors can lead to localized overheating, inefficient heat absorption, increased carbon-in-ash, and accelerated tube failures—especially in the superheater sections.

Combustion uniformity in pulverized coal boilers is critical for maintaining overall thermal efficiency and preventing hot spots [4]. Variations in coal flow distribution among burners, often caused by pipe geometry inconsistencies, wear in mechanical orifices, and uneven primary air supply, can disrupt the balance of the fireball formation [5]. Consequently, imbalanced fireball distribution elevates the risk of slagging and shortens the service life of furnace components.

Coal Velocity Balancing (CVB) has emerged as a practical solution to these issues. By adjusting the velocity of coal particles through mechanical orifice tuning, flow uniformity among the burner pipes can be restored. This paper investigates the application of the CVB method in conjunction with Computational Fluid Dynamics (CFD) simulations to analyze and optimize the combustion characteristics of a full-scale pulverized coal furnace operating under 100% LRC conditions [8].

A case study was conducted at Rembang CFPP 300 MW, focusing on diagnosing and correcting fireball asymmetry through CFD-based thermal analysis before and after coal velocity adjustments [9]. The objective is to validate CVB as a tool not only for improving combustion efficiency but also for reducing thermal stress on critical components, particularly the superheater, under challenging coal switching scenarios.

2. Materials and methods

The research is structured into two major phases:

A. CFD Modeling of Furnace Combustion and Fireball Condition

To evaluate fireball behavior and thermal distribution inside the furnace under 100% Low-Rank Coal (LRC) firing, a three-dimensional Computational Fluid Dynamics (CFD) simulation was performed using ANSYS Fluent [8]. A detailed geometric model of the PLTU Rembang boiler was developed based on actual plant dimensions, including burner arrangement, primary and secondary air flow paths, and pulverized coal injection parameters.

The simulations were conducted under full-load LRC operating conditions to visualize combustion flow patterns, flame development, fireball formation, and temperature gradients throughout the furnace [4]. Special attention was given to the interaction between the fireball and the superheater region in order to assess the potential overheating risk [10].

The main objectives of the CFD simulation were to :

- Visualize temperature contours across both vertical and horizontal furnace cross-sections.
- Identify the dominant fireball zone, defined as the region with the highest thermal intensity.
- Analyze the influence of coal velocity imbalance on combustion stability and flame symmetry.

B. On-Site Mechanical Orifice Inspection and Adjustment Velocity Balancing Procedure

Field measurements were conducted to obtain baseline operational data, including flue gas temperature, furnace exit gas temperature (FEGT), and furnace wall temperatures at different burner elevations. These measurements were used to validate the CFD results and to identify indications of combustion imbalance [9], [10].

The objectives of the mechanical inspection and adjustment phase were to:

- Inspect and repair mechanical orifices exhibiting erosion, clogging, or dimensional deviation.
- Adjust mechanical orifices for each pulverized coal pipe to improve velocity uniformity.

Coal Velocity Balancing (CVB) was implemented by adjusting mill inlet pressures and modifying orifice plate openings to equalize coal velocities across all burner pipes. The target velocity was set at approximately 3300 feet per minute (fpm), in accordance with the boiler design specification. An isokinetic coal flow measurement system was utilized to monitor velocity distribution and ensure proper balancing [7].

To guarantee effective coal flow redistribution, mechanical orifices in each coal pipe were inspected and adjusted following the standard operating procedure described below

The standard operating procedure is as follows:

1. Preparation
   - Review coal flow test reports.
   - Identify coal pipes with significant velocity deviations.
2. Inspection
   - Dismantle orifice flange.
   - Inspect the physical condition of the orifice (erosion, blockage, deformation).
   - Measure orifice diameter.
3. Adjustment
   - Modify the orifice opening by selecting a smaller or larger diameter based on the measured velocity deviation.
   - Reinstall and torque the flange connections according to standard specifications.
4. Verification
   - Re-measure coal flow velocities after adjustment using an isokinetic probe system.
   - Confirm that the velocity variation among all pipes is within ±5%.

3. Results and discussion

This section presents the results obtained from the Computational Fluid Dynamics (CFD) simulations, on-site coal velocity balancing implementation, and post-adjustment operational evaluation. The discussion focuses on fireball behavior, coal flow distribution uniformity, and the resulting impact on boiler thermal performance and superheater protection.

3.1. CFD Analysis of Fireball Distribution Before Orifice Adjustment

The first CFD simulation, as illustrated in Fig. 1, presents the temperature distribution on a horizontal plane of the furnace under full-load operation with 100% Low-Rank Coal (LRC). The temperature contours demonstrate a distinctly non-uniform fireball structure, where high-temperature regions exceeding 1300 °C are concentrated toward two diagonal corners of the combustion chamber. In contrast, other zones exhibit significantly lower temperatures below 800 °C, indicating areas of incomplete combustion [3], [4].

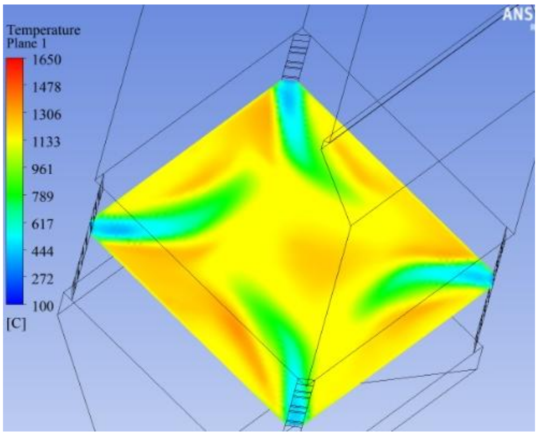


Figure 1. Fireball Unbalance (Actual Condition)

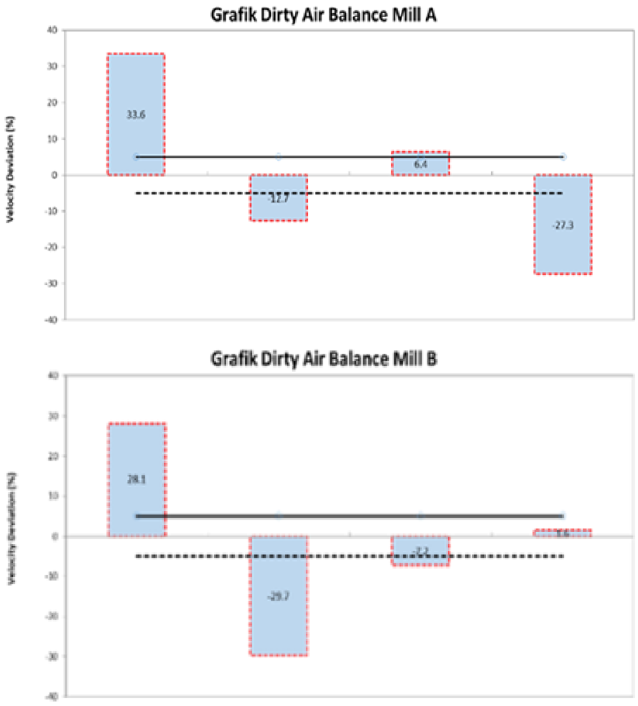
This pronounced thermal asymmetry indicates a strong imbalance in the coal–air distribution among the burners, which is primarily associated with deviations in coal pipe velocities [5], [6]. Contributing factors include mechanical orifice wear, inaccurate flow area calibration, erosion of burner nozzles, and uneven primary air supply [5], [7]. The off-centered fireball leads to localized overheating on specific furnace wall sections, thereby accelerating slagging formation and thermal fatigue of boiler components, while cooler zones promote incomplete combustion and increase unburned carbon losses in fly ash [3], [6].

The regions with the highest temperature, ranging from 1300 °C to above 1600 °C (represented by red-to-yellow contours), are asymmetrically concentrated along two diagonal furnace corners. Conversely, the lower-right and upper-left regions display significantly lower temperature levels, as indicated by blue and green contours below 800 °C. This pronounced temperature gradient confirms that the fireball is displaced from its optimal centrally aligned position [4], [9].

Such an off-centered fireball configuration is a clear indicator of combustion maldistribution, which is commonly caused by unequal coal–air flow delivery to individual burners [5], [7]. These imbalances are typically associated with non-uniform coal pipe velocities resulting from worn or improperly adjusted mechanical orifices, coal nozzle degradation, and unstable mill operational characteristics [6], [10].

3.2. Coal Balancing Distribution Before Orifice Adjustment

This subsection presents the baseline condition of pulverized coal flow distribution among burner pipes prior to mechanical orifice adjustment, highlighting the initial level of velocity imbalance that contributed to non-uniform combustion behavior.



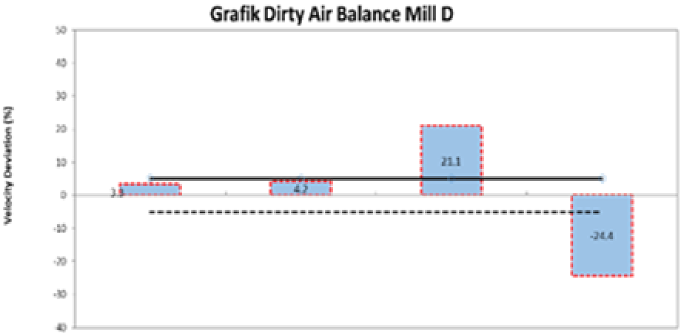


Figure 2. Coal balancing Mill A, B and D before Adjustment

The results of the Coal Velocity Balancing on Unit 10 indicate that the airflow distribution across the pulverizers (Mill A, B and D) is non-uniform, with velocity deviations from the average ranging between -27.3 % and +33.6 %. This imbalance suggests varying flow resistance within each coal burner pipe, which may be attributed to pipe geometry, nozzle wear, or internal fouling. Such conditions potentially lead to uneven coal distribution, destabilization of the flame, increased slagging risk, and overheating of the superheater tubes. Consequently, corrective measures are necessary, including mechanical balancing of coal velocity and the application of Computational Fluid Dynamics (CFD) simulations, to ensure combustion efficiency and boiler operational reliability—particularly during transitions to low-rank coal usage.

3.3. On-Site Mechanical Orifice Inspection and Adjustment

First step, inspect and repair all mechanical orifice in Pulverized, verify position measurement.

The inspection of mechanical orifices within pulverized coal pipes revealed wear, erosion, and build-up of unburned coal residues which contributed to uneven distribution and velocity variations.

Figure 3. Visual Condition of Mechanical Orifice Before Maintenance

The orifices were cleaned, resized, or replaced as necessary to restore flow uniformity. This process ensured consistent fuel distribution, which is critical for achieving balanced combustion and minimizing localized overheating.

Figure 4. Repair and Installation of Mechanical Orifice After Maintenance

Once all mechanical orifices had been repaired and thoroughly cleaned, coal velocity balancing was conducted to achieve uniform pulverized coal distribution across all burner pipes.

Figure 5. Coal balancing Adjustment using Isokinetic Coal Balancing

3.4. Coal Balancing Distribution After Orifice Adjustment

Fig. 6 illustrates the distribution of coal flow across each coal pipe for Pulverizer A, B, and D, before and after the application of the coal velocity balancing method. The data is presented using boxplots to highlight the variability and uniformity of coal distribution among the individual pipes. In Pulverizer A, the coal mass flow among the four pipes prior to innovation shows a noticeable variance, with several pipes receiving more coal than others, as indicated by the presence of outliers and a wide interquartile range.

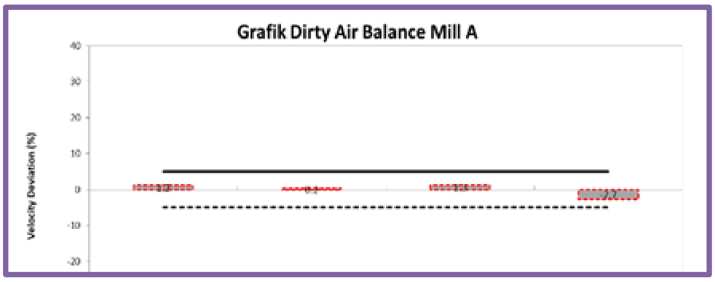


Figure 6. Coal balancing Mill A, B and D After Adjustment

After the implementation of the balancing method, the distribution becomes significantly more uniform, and the outliers are reduced, indicating improved flow symmetry and balanced coal delivery to the burners. The coal flow balance for Pulverizer B. Prior to innovation, certain pipes exhibit higher deviations from the mean flow, suggesting inconsistent fuel supply and potential combustion inefficiencies. Post-innovation results demonstrate a more centralized distribution with minimal dispersion, highlighting the success of the velocity balancing approach in equalizing fuel flow rates across all discharge pipes. For Pulverizer D, where similar improvements are observed. The pre-innovation condition displays moderate variability and unequal distribution among the pipes. After the balancing intervention, the flow becomes more consistent across all lines, with a noticeable decrease in maximum and minimum deviations, suggesting enhanced control over coal particle velocity and trajectory within the pulverizer system. Overall, the reduction in flow imbalances across all pulverizers confirms that the coal velocity balancing method is effective in achieving more even coal distribution. This uniformity is essential for stabilizing combustion in the furnace, minimizing localized hot spots, and preventing superheater overheating — particularly in coal switching applications where variations in coal properties can disrupt flow dynamics.

3.5. Operation Parameter Improvement

Fig. 7 presents the comparative trend of outlet flue gas temperatures at locations A and B before and after the application of the coal velocity balancing method. The solid lines indicate the baseline temperature profiles for FG A and FG B, while the dashed lines illustrate the profiles post-optimization.

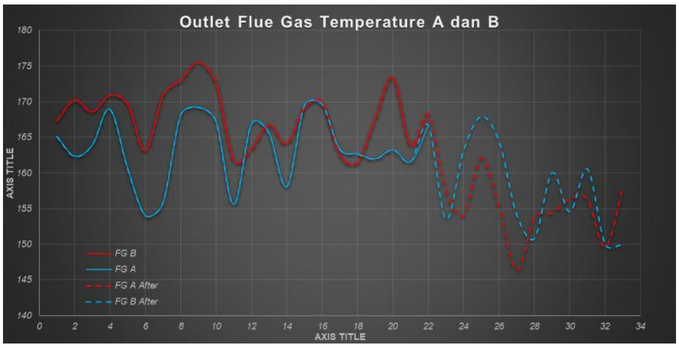
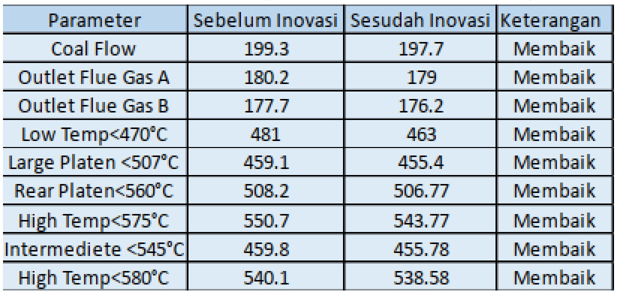


Figure 7. Outlet Gas Temperature Result After Adjustment

A notable improvement is observed post-implementation, particularly in the reduction of peak temperatures and the harmonization of temperature fluctuations across both paths. This suggests enhanced combustion uniformity and improved thermal distribution, which are critical in preventing localized overheating in the superheater section. The temperature variation post-adjustment becomes more stable, indicating a successful reduction in combustion imbalance—a common issue when switching between different coal types. The CFD analysis supports these findings by showing improved flow uniformity and reduced thermal deviation, validating the effectiveness of the velocity balancing strategy in optimizing boiler performance and protecting critical heat exchange surfaces.

Table 1. Outlet Gas Temperature Result After Adjustment



Parameter	Sebelum Inovasi	Sesudah Inovasi	Keterangan
Coal Flow	199.3	197.7	Membaik
Outlet Flue Gas A	180.2	179	Membaik
Outlet Flue Gas B	177.7	176.2	Membaik
Low Temp<470°C	481	463	Membaik
Large Platen <507°C	459.1	455.4	Membaik
Rear Platen<560°C	508.2	506.77	Membaik
High Temp<575°C	550.7	543.77	Membaik
Intermediete <545°C	459.8	455.78	Membaik
High Temp<580°C	540.1	538.58	Membaik

Table 1 summarizes the operational performance indicators before and after the implementation of the coal velocity balancing method. As shown, all measured parameters exhibited improvement, indicating the effectiveness of the innovation in enhancing boiler combustion stability.

Coal flow rate slightly decreased from 199.3 tons/hour to 197.7 tons/hour, suggesting improved fuel efficiency without compromising thermal output. The outlet flue gas temperatures at points A and B also declined from 180.2°C to 179°C and from 177.7°C to 176.2°C, respectively. This reduction indicates better combustion uniformity and a more balanced heat distribution across the system.

Significantly, temperature readings across critical superheater regions showed reductions in the number of high and low thermal zones. This includes the Low Temperature Region (<470°C), Large Platen (<507°C), Rear Platen (<560°C), High Temperature Zone (<575°C), and Intermediate Region (<545°C). These improvements are essential for minimizing localized overheating risks, thus prolonging the lifespan of heat exchange surfaces.

Overall, the reduced temperature deviation across the boiler surfaces following the innovation confirms the success of the velocity balancing method. This is further validated by CFD simulation results, which demonstrate improved uniformity in velocity and thermal distribution, reinforcing the strategy's effectiveness in optimizing combustion while preventing superheater overheating during coal switching applications.

5. Conclusion

This study confirms that the integration of Coal Velocity Balancing (CVB) and CFD-based fireball analysis is effective in improving combustion stability and preventing superheater overheating during 100% Low-Rank Coal (LRC) operation. Mechanical orifice adjustments applied to pulverizers A, B, and D significantly reduced coal flow maldistribution and restored velocity uniformity across burner pipes, as validated through both numerical simulation and field measurements. The improved flow distribution led to lower and more uniform outlet flue gas temperatures, indicating reduced thermal stress on critical boiler components. A slight reduction in coal consumption was also observed without sacrificing boiler load, demonstrating enhanced combustion efficiency.

The main contribution of this work lies in the practical integration of CFD-based fireball diagnostics with on-site coal velocity balancing as an effective preventive strategy for boiler overheating under coal switching conditions. This approach provides a replicable and cost-effective framework for improving operational reliability in pulverized coal-fired power plants. Future studies should focus on implementing real-time adaptive flow control systems to further enhance combustion performance under variable fuel characteristics.

References

[1] M. Zhang, Y. Li, and H. Wu, “Fuel switching strategies in coal-fired power plants: Economic and operational perspectives,” Energy Policy, vol. 148, pp. 1–10, 2021.

[2] K. R. Bhattarai and T. H. Ko, “Combustion characteristics of low-rank coal in pulverized coal-fired boilers,” Fuel, vol. 262, pp. 1–12, 2020.

[3] A. Smith and D. P. Jones, “Failure mechanisms of superheater tubes under fluctuating thermal loads,” Engineering Failure Analysis, vol. 115, pp. 1–14, 2020.

[4] J. Zhang, L. Wang, and X. Chen, “Effect of coal distribution on combustion uniformity in large utility boilers,” Applied Thermal Engineering, vol. 145, pp. 159–169, 2018.

[5] R. K. Mohanty and S. K. Das, “Influence of coal pipe geometry and primary air imbalance on burner performance,” Energy Conversion and Management, vol. 186, pp. 521–531, 2019.

[6] P. Verma, A. Kumar, and N. Singh, “Slagging and fouling behavior in pulverized coal boilers under asymmetric firing,” Fuel Processing Technology, vol. 191, pp. 89–98, 2019.

[7] C. F. Jensen and M. Eriksson, “Coal velocity balancing techniques for improved combustion stability in pulverized coal furnaces,” Journal of Energy Engineering, vol. 146, no. 4, pp. 1–11, 2020.

[8] S. R. Turns, An Introduction to Combustion: Concepts and Applications, 3rd ed. New York, NY, USA: McGraw-Hill, 2012.

[9] I. R. Hidayat, A. Prasetyo, and M. Wibowo, “CFD-based fireball diagnostics for burner imbalance detection in large-scale coal boilers,” International Journal of Thermal Sciences, vol. 171, pp. 1–13, 2022.

[10] Y. Liu, Z. Zhou, and H. Chen, “Thermal stress mitigation of superheater tubes under fuel switching operation,” Applied Energy, vol. 274, pp. 1–12, 2020.