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Numerical Analysis of Fluid Flow Characteristics in Coal–Woodchips Combustion Within a Circulating Fluidized Bed Furnace (Case Study: Up Sebalang)

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ABSTRACT

The increasing energy demand in the era of Industry 4.0 is driving the transition towards renewable energy, yet Indonesia's dependency on coal remains high. One promising decarbonization strategy is the high co-firing technology, which involves mixing biomass (such as woodchips) with coal in coal-fired power plant boilers. Previous studies have generally focused on emission and combustion efficiency aspects without delving deeply into the fluid flow characteristics within the furnace. Therefore, this study aims to numerically analyze the fluid flow characteristics in the combustion process of coal and woodchip mixtures in the Circulating Fluidized Bed (CFB) boiler of the UP Sebalang Power Plant. The method used is Computational Fluid Dynamics (CFD) simulation with a multiphase Eulerian model, k-ε turbulence model, and discrete phase for coal particle injection. The simulations were performed for three fuel variations: 100% coal, 90% coal + 10% woodchips, and 80% coal + 20% woodchips. The results show that increasing the woodchip proportion lowers the average temperature in the furnace from 945°C to 810°C, causing uneven heat distribution. The pressure distribution also decreases with the increasing woodchip fraction, with negative pressure at the cyclone outlet increasing from -310 Pa to -401 Pa. Validation of the simulation results against field data shows an average deviation of 2–9%, which is within tolerance limits, although affected by measurement tool imperfections and model limitations regarding the effects of the induced draft fan.

KEYWORDS *co-firing, numerical simulation, fluidization, biomass, Circulating Fluidized Bed (CFB), simulation validation, woodchips*

INTRODUCTION

In the era of Industry 4.0, the demand for electrical energy continues to rise alongside the growth of the household, business, and industrial sectors. However, Indonesia still relies heavily on fossil fuels such as coal, petroleum, and natural gas as the main sources of electrical energy (Dutu, 2016; Hartono et al., 2020; Hodžić et al., 2016; Roni et al., 2017). To reduce this dependency, the government has targeted a national energy mix with 23% of total energy coming from renewable energy sources by 2025. Despite this, in 2020, the contribution of renewable energy was still low, only around 11.20%, while coal remained dominant at 38.04% (Personal, 2021). Therefore, an effective strategy is needed to increase the use of renewable energy to achieve the set targets (Agbor et al., 2014; Hasan et al., 2012; Huang et al., 2017; Pandey et al., 2023; Tymoshenko et al., 2022).

One promising solution is the application of high co-firing, which is a method of mixing biomass with coal in the combustion process in coal-fired power plant boilers. This method allows for a reduction in coal consumption as well as greenhouse gas emissions without sacrificing the efficiency of power generation (Wander et al., 2020). In addition, high co-firing can reduce the cost of electricity production and serve as an alternative for the transition to more environmentally friendly energy (Xu et al., 2020). In this context, woodchips-based biomass is one of the potential fuels used in high co-firing schemes because of its abundant availability and its more environmentally friendly impact compared to coal.

PLN Nusantara Power has implemented the Green Co-Firing program as part of its decarbonization strategy. In 2023, the realization of energy production from co-firing reached 529,662.50 MWh, or 112.29% of the set target. Meanwhile, the target for using woodchips biomass nationally in 2024 has been increased to 1,088,657.76 MT, an increase of 201.34% from the previous year (Indarto, 2024). In line with this effort, PT PLN Nusantara Power UP Sebalang is planned to conduct a high co-firing trial of biomass woodchips with various mixing ratios and numerical simulations using *CFD* (Alekseenko et al., 2019; Karampinis et al., 2016; Triani et al., 2022; Zhou et al., 2011).

Previous studies have explored various strategies to reduce dependency on fossil fuels, with a notable focus on the use of renewable energy and the implementation of co-firing in coal power plants. Wander et al. (2020) demonstrated that high co-firing with biomass can significantly reduce coal consumption and greenhouse gas emissions, while maintaining the efficiency of power generation. This study, however, primarily focused on the environmental impacts and overlooked the detailed optimization of combustion processes and fluid flow characteristics within the furnace, which are critical for maximizing the efficiency of the co-firing process. Similarly, Xu et al. (2020) discussed the potential cost reductions associated with co-firing, emphasizing economic benefits but lacking in-depth analysis of the combustion dynamics in coal-fired boilers. While these studies provide valuable insights into the environmental and economic advantages of co-firing, they do not adequately address the technical challenges involved in optimizing fluidization and combustion efficiency in coal-fired power plants.

This research fills these gaps by focusing on the numerical simulation of fluid dynamics in the combustion process of coal and biomass mixtures, particularly using woodchips-based biomass. The application of *Computational Fluid Dynamics* (*CFD*) in this study is a novel approach that goes beyond environmental and economic perspectives by directly addressing the technical optimization of co-firing. By analyzing factors such as temperature, pressure, air distribution, and material circulation in the furnace, this study aims to optimize the high co-firing process, providing more detailed insights into the thermal performance of the combustion process and its optimization potential.

The objective of this study is to analyze the fluid flow characteristics in coal-fired power plant furnaces using a high co-firing method with woodchips-based biomass. By conducting numerical simulations using *CFD*, this research aims to optimize the thermal performance of the combustion process and provide insights into improving the efficiency of co-firing systems. This study will benefit the energy sector by offering valuable data for optimizing co-firing techniques, improving the economic feasibility of renewable energy integration, and supporting Indonesia's national energy mix targets.

This trial aims to analyze the characteristics of fluidization, including the distribution of temperature, pressure, air, and materials in the furnace, in order to optimize the implementation of high co-firing in coal-fired power plants based on fluid circulation. This research will focus on the numerical analysis of fluid flow characteristics in coal-fired power plant furnaces using woodchips-based high co-firing methods, providing insights into thermal performance and optimization potential in the combustion of coal and biomass mixtures.

RESEARCH METHOD

Surveyors and Mesh

In numerical simulations, creating accurate simulation domains is critical because it directly influences the validity and reliability of the simulation results. This study's domain includes several important components, such as the mass flow inlet for primary water at the bottom of the furnace, secondary water supplied through four pipes on the front side (front furnace) and four pipes on the rear side (rear furnace), as well as the coal injection system, which is carried out through four pipes. Additionally, high-pressure air is introduced through two pipes on the cyclone side and at the bottom of the furnace. These components define the flow characteristics of the system and are crucial in understanding the thermal and fluid behavior inside the furnace.

Meshing Process and Simulation Domain

Meshing plays an essential role in dividing the simulation domain into smaller, manageable volumes, which enables precise discretization of the domain for solving the governing equations. This division is important because it allows the system to calculate the flow and thermal dynamics more accurately. Meshing needs to be carefully designed to ensure that the selected mesh matches the expected flow pattern and provides a high-quality simulation result. In this study, the meshing process utilizes the automatic method with tetrahedron elements, and the maximum face size is set to 0.2 meters. This configuration results in a total of 634,631 nodes and 3,332,863 elements. The chosen meshing resolution and method ensure that the simulation accurately captures the behavior of the fluid dynamics, temperature distributions, and other relevant parameters in the furnace.

Data Collection

The data collection technique for this study involves both experimental measurements and computational simulations. Experimental data is collected through field measurements at the UP Sebalang Power Plant. Temperature and pressure data at various points in the furnace are obtained, as well as data on coal flow rates and air injection parameters. These measurements are taken during actual co-firing operations with different biomass-to-coal ratios (100% coal, 90% coal + 10% woodchips, and 80% coal + 20% woodchips).

Additionally, data from the numerical simulations are gathered by running *CFD* models using a comprehensive set of input parameters such as coal and biomass characteristics, air flow rates, and combustion conditions. The simulation data are then compared with the field measurement data to validate the model's accuracy and reliability.

Data Analysis

Data analysis for this study involves both qualitative and quantitative methods. The primary quantitative method is the comparison of the simulation results (including temperature, pressure, and velocity distributions) with field measurement data. Statistical techniques, such as average deviation analysis and error quantification, are used to assess the degree of accuracy and identify any discrepancies between simulated and real-world data. A tolerance limit of 2–9% is considered acceptable for model validation, acknowledging potential inaccuracies due to the measurement tool limitations and the inherent assumptions of the *CFD* model. In addition to this, the sensitivity of the simulation results to various input parameters such as biomass-to-coal ratio, air injection pressure, and coal characteristics is analyzed using parametric studies. These studies help to determine the optimal co-firing ratio that maximizes thermal performance and minimizes negative impacts such as uneven heat distribution or excessive pressure fluctuations.

Furthermore, post-processing tools in *CFD* are used to visualize the results and interpret the fluid dynamics and heat transfer characteristics in the furnace. Temperature and pressure distribution maps are created to visualize hotspots and identify potential areas for system optimization. The results from these analyses guide the next steps in optimizing the co-firing process for improved thermal efficiency and safety in coal-fired power plants.

RESULT AND DISCUSSION

Checking the Geometry Model and Validation Location

Before running the main simulation on the Circulating Fluidized Bed (CFB) boiler, geometry verification (figure 2a) is carried out to ensure that each part is properly connected. This verification is carried out through an initial simulation by inserting airflow through the primary and secondary air inlets, then analyzed using a pathline. Geometry is considered valid if the pathline indicates that the airflow flows from the inlet to the outlet and circulates well through the furnace and cyclone. This step ensures that the model configuration is appropriate before further analysis.

Validation is carried out by comparing the simulation results with actual data in the field. In this study, nine validation points were selected based on strategic locations in the system, namely:

1) One point above the furnace nozzle.
2) Two points on the furnace at a height of 35 meters (right and left sides).
3) Two points above the cyclone (right and left sides of the output furnace).
4) Two points on the cyclone output.
5) Two points on the return flow path to the furnace.

The selection of these points provides a comprehensive picture of the distribution of the parameters being tested, so that the comparison between the simulation results and real conditions can be made more accurately. Details of the location of the validation points can be seen in figure 1b and table 1.

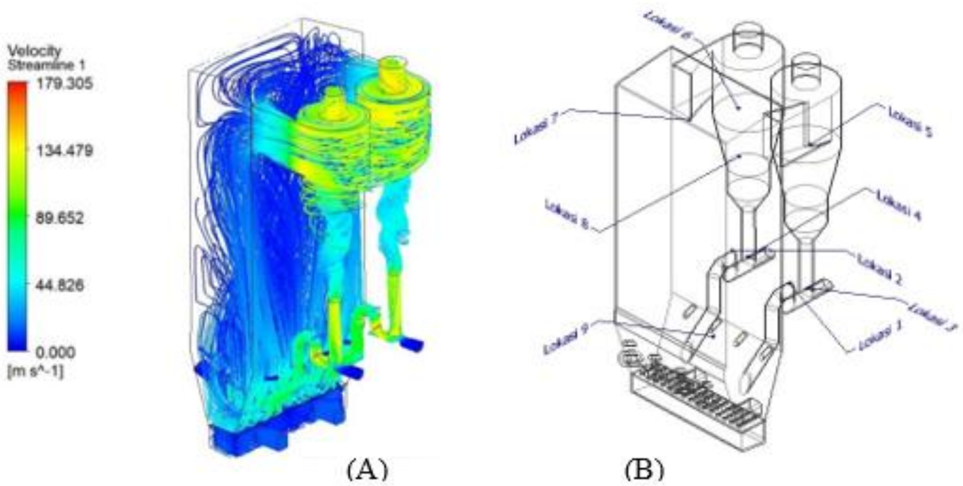

Figure 1. (A) Checking the Geometry Model, (b) Validation Location

Table 1. Validate Temperature and Pressure

		Location								
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Temperature (^{0}C)	Simulasi Bb 100%	893,7	890,6	880,1	875,7	992,4	990,6	989,2	990,1	993,6
	Simulasi Bb 90% Wc 10%	803,2	802,5	811,34	805,68	890,3	885,9	880,4	884,9	889,9
	Simulasi Bb 80% Wc 20%	782,7	780,5	805,39	797,54	841.3	844,2	838,3	830,8	841,3
	Actual Bb 100%	1026	890	973	947	971	960	950	968	974
	Actual Bb 90% Wc 10%	1014	890	901	894	956	946	923	938	960
	Actual Bb 80% Wc 20%	1010	890	892	884	930	913	904	916	934
Pressure (Pa)	Simulation Bb 100%	248,1	242,8	255,1	250,4	-93,2	-103,1	401,3	400,7	410,2
	Simulation Bb 90% Wc 10%	230,4	228,3	210,8	203,7	-86.8	-82.47	387,3	385,7	390,4
	Simulation BB 80% WC 20%	93,8	91,6	88,4	90,2	-71,6	-64,3	187,5	187,2	189,8
	Actual Bb 100%	300	289	301	290	-284	-310	-302	-272	524
	Actual Bb 90% Wc 10%	293	282	300	278	-293	-355	-348	-283	519
	Actual Bb 80% Wc 20%	280	270	281	262	-329	-373	-360	-280	492

Temperature Distribution

Figure 1 shows the temperature distribution in the combustion chamber in three different fuel composition scenarios. In Figure 2 [A], the use of 100% coal results in high and even temperatures across almost all combustion chamber volumes, with an average value of 945 °C. The dominant red and yellow colors in the middle to the top of the combustion chamber indicate that combustion takes place evenly and efficiently. In Figure 2 [B], when the fuel mixture consists of 90% coal and 10% woodchips, the temperature distribution begins to show irregularities. There were blue and green zones at the bottom of the furnace indicating local cooling, and the average temperature dropped to about 850 °C. This inhomogeneity reflects an imbalance in combustion due to differences in thermal characteristics between fuels. Meanwhile, Figure 2 [C] with a composition of 80% coal and 20% woodchips shows an increasingly non-uniform distribution of heat, with a predominance of blue-green in most areas of the combustion chamber and an average temperature of only about 810 °C. This phenomenon suggests that an increase in the proportion of woodchips leads to disturbances in combustion stability and heat transfer efficiency. In addition, the area of active combustion appears to be more limited and unevenly distributed, which indicates that imperfect mixing of fuels leads to suboptimal heat flow patterns.

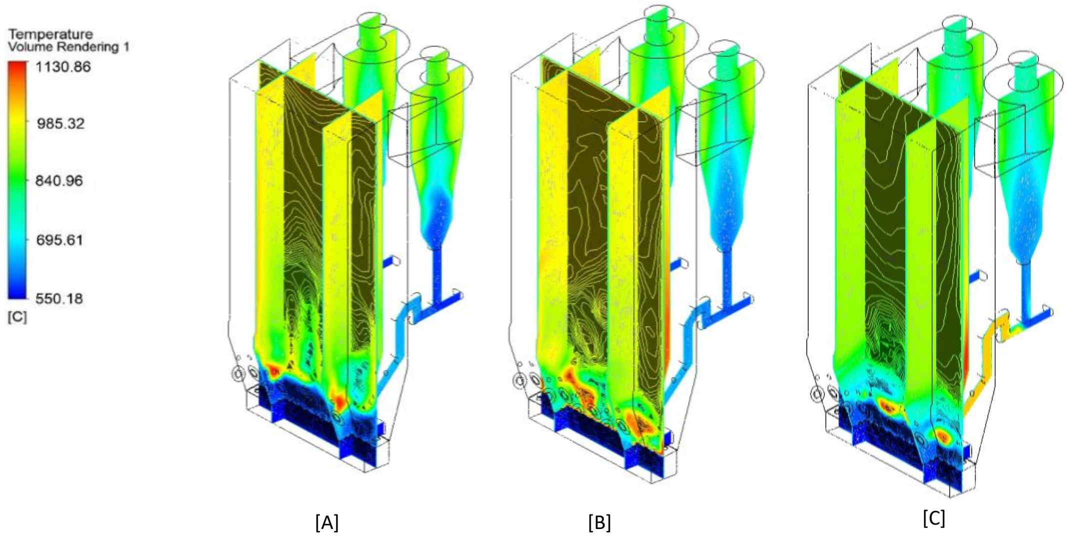

Figure 2. Temperature Distribution Contours [A] BB 100%, [B] Coal 90% Woodchips 10%, [C] Coal 80% Woodchips 20%

Furthermore, the quantitative validation results in Table 1 show that the difference between the simulation results and the actual data varies at each measurement point. In the 100% coal usage scenario, the biggest difference occurs at point 1 with a difference of 12.89%, while the other point shows a smaller deviation, mostly below 5%. For a mixture of 90% coal and 10% woodchips, the largest difference occurs at point 1 at 20.79%, while other points tend to have a fairly low deviation, such as 2.22% at point 5. Meanwhile, in the 80% coal and 20% woodchips scenario, the most significant deviation value appears at point 9 of 9.93%. Despite the variation in deviation values, the majority of the differences remained within the tolerance limit of less than 10%, which supported the model's accuracy. Significant nonconformities were recorded at validation point one, where the actual temperature was recorded exceeding 1000 °C, and validation point two (left-side sealpot), where the temperature was stagnant at 890 °C without fluctuations. Further investigation revealed that this discrepancy was caused by thermocouple damage, so the data obtained was inaccurate and could not be used as a reference in model validation.

This indicates that the trend of the simulation results is in line with the actual data trends, although there are differences that vary from location to location, namely the value of the percentage range of differences between the simulation data and the actual data ranges from 2%–9%. This is in line with research conducted by Smith, J.A. & Brown, R.C. (2020), which emphasizes the importance of temperature distribution evaluation and comparison between the two types of data to improve the efficiency of analysis. The study also stated that the permissible difference value should be kept below 10%, so that the accuracy of the simulation results is maintained. Thus, the simulation model used in this study can be considered to have sufficient validity to describe the temperature distribution in the combustion chamber.

Pressure Distribution

In Figure 3, you can see the difference in the contour of the pressure distribution in the combustion chamber due to variations in fuel composition. In Figure 3 [A] (100% coal), the pressure distribution averages 224 Pa, while at cyclone outlets it is negative (-310 Pa). In Figure 3 [B] (90% coal, 10% woodchips), the average pressure drops to 207 Pa, with a cyclone outlet pressure of -327 Pa. In Figure 3 [C] (80% coal, 20% woodchips), the average pressure is lower (88 Pa) and the cyclone outlet pressure is increasingly negative (-401 Pa).

This decrease in pressure is caused by changes in flow characteristics in circulating fluidized beds (CFBs). The higher the proportion of woodchips, the lower the fuel density and combustion rate, which decreases the pressure distribution in the combustion chamber. In addition, the increase in woodchips increases the drag force, so that the pressure at the cyclone outlet becomes more negative.

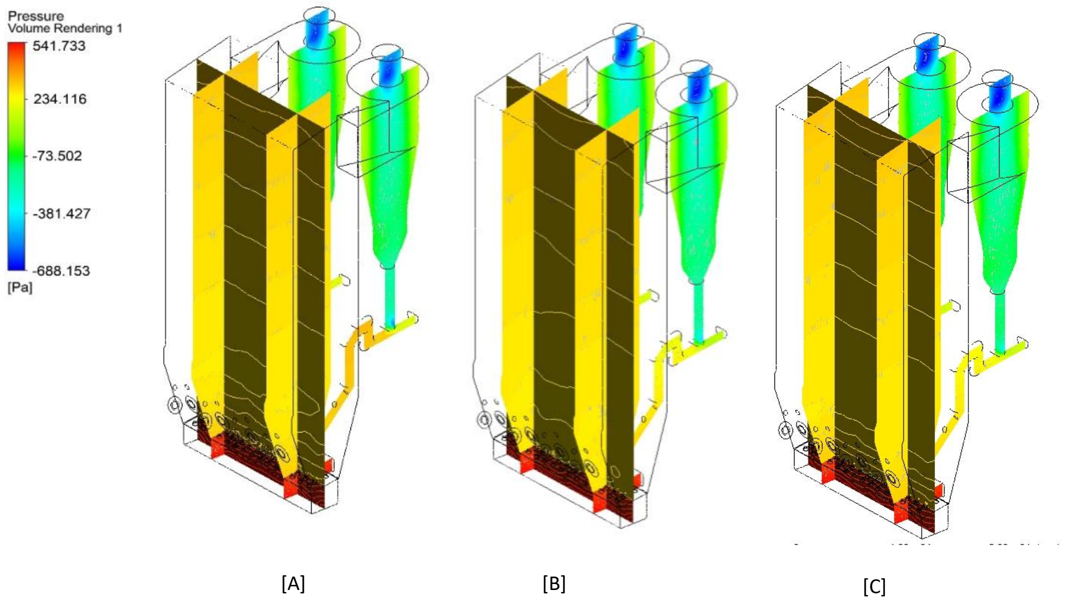

Figure 3. Temperature Distribution Contours [A] BB 100%, [B] Coal 90% Woodchips 10%, [C] Coal 80% Woodchips 20%

Table 1 shows a striking difference between the simulation results and direct field measurements at various pressure measurement points within the boiler's Circulating Fluidized Bed (CFB) system. This difference arises due to various factors, including the mechanism of particle fluidization, gas flow patterns, and air injection and suction systems. These factors play a significant role in influencing the pressure distribution in the furnace.

At certain validation points, such as the lower furnace area (location 9), the pressure of the simulation results and field validation has a similar tendency, i.e. higher. This is due to the accumulation of bed material and air impulse from the primary air fan, which is the main source of particle fluidization. However, at higher points, such as location 7 and location 8, the pressure decreased significantly on field validation compared to the simulation results. This decline was mainly influenced by the expansion of combustion gases, increased gas flow speeds, as well as the suction effect of the induced draft fan (IDF). The simulation results tend to show a less sharp decline, which indicates that the simulation model has not fully captured the effects of the complex interactions between the gas and the IDF.

In contrast, in the area of the cyclone outlet and exhaust gas line (location 5 and location 6), the pressure tends to be negative in field measurements due to the pull from the IDF. Meanwhile, in the simulation results, although there was a decrease in pressure, the value was not as deep as the results of field validation. The research of Kumar, A., and Gupta, R. (2018) and Wang, X., and Li, Y. (2021) supports these findings, noting that simulation models often do not consider the complex interactions of gas flows with different types of fans, including IDF. The research of Zhao, Y., and Zang, L. (2020) also emphasizes that fan configurations that are not fully covered in the simulation can result in significant differences between the simulation results and actual conditions.

Overall, pressure fluctuations in the furnace are influenced by a combination of factors, such as the circulation of solid particles, the fluidization mechanism, the rate of combustion reaction, and the effect of the fan, especially the IDF. The comparison graph in Figure 3 provides a more detailed picture of the pressure trends at each validation point, helping to explain the difference in pattern between the simulation results and the actual measurements. Improvements to the simulation model, taking into account the direct effects of the IDF and interaction between fans, are needed to improve the accuracy of the simulation results so that they are closer to actual conditions in the field.

CONCLUSION

The addition of woodchips to the fuel mixture significantly impacts both the temperature and pressure distribution within the furnace. As the proportion of woodchips increases, the average temperature decreases and becomes more uneven, indicating reduced combustion stability. For instance, with a 90% coal and 10% woodchip mixture, the temperature drops to 850°C, and with 20% woodchips, it further decreases to 810°C. Similarly, the pressure distribution also reflects a decline in average pressure as the woodchip ratio increases, with the negative pressure at the cyclone outlet becoming more pronounced. Validation of the simulation results against actual data showed an average deviation of 2%–9%, with the largest discrepancies attributed to measurement inaccuracies. Although there were some deviations in both temperature and pressure due to limitations such as the exclusion of the suction effect of the induced draft fan and the back pass area, the simulation results still demonstrated a consistent downward trend, making the model useful for estimating the impact of fuel ratios on system performance. For future improvements, further refinement of the model could include more precise measurement techniques, incorporating all factors such as the suction effect of the fan and other dynamic elements like ash buildup in the furnace, to improve accuracy and better inform *co-firing* strategies.

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