Numerical Study of the Effect of Air-Fuel Ratio (AFR)on Flow and Combustion Characteristics in Burners Tangentially Fired Pulverized Coal Boiler

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Abstract. A 3D numerical simulation analyzed combustion in a pulverized coal boiler with tangential firing, optimizing mixing for more complete combustion. Adjusting the air-fuel ratio (AFR) was vital, with AFR values of 5.84, 6.15, 6.47, 6.79, 7.44, and 8.09. Computational Fluid Dynamics (CFD) investigated velocity, temperature, and O2, CO2, and CO species distributions. Standard k-ε turbulence modeling, a discrete phase model for coal particles, a species transport model for combustion, and a Discrete Ordinates model for radiation were employed. Results showed turbulent flow and ideal particle trajectories in the burner. Higher AFR increased flue gas velocity but decreased temperature. At AFR 5.84, O2 was lowest and CO2 highest, indicating optimal stoichiometric oxidation. Extremes in AFR caused unburned carbon due to poor air-coal mixing. AFR 5.84 was identified as optimal for efficient combustion.

Keywords: Combustion Efficiency; Tangentially Fired Pulverized Coal Boiler; Computational Fluid Dynamics; Air-Fuel Ratio; Fire-ball.

1. Introduction

A pulverized coal boiler with tangential combustion has advantages in mixing fuel and air well so that combustion occurs almost perfectly and the temperature distribution is more even. Important parameters must be considered so the boiler can operate optimally, efficiently, and reliably. Among the parameters that must be regarded in boiler operation are primary air, secondary air, coal, and others. Changes in the amount of secondary air can directly affect operating conditions.

The primary function of air in the combustion process is as a provider of oxygen. In secondary air, the incoming air will be used as combustion air. Staging air will be formed by separating primary and secondary air, and the combustion temperature will change. The amount of secondary air entering the boiler can affect its flow characteristics. The addition of secondary air can affect the turbulence during the combustion process. With changes in the amount of secondary air, the air-fuel ratio (AFR) value will also change [1].

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In increasing the reliability and efficiency of the boiler to ensure that the combustion process occurs well, there is not much unburned carbon, the fireball that is formed, and the heat transfer that happens will be safe (overheating occurs). Direct inspection of boiler components can be carried out in the field. However, errors when determining variable changes in operatingconditions pose a risk to the safety of the generating unit. To anticipate this, other methods are needed that are more flexible and safer without directly affecting operating conditions. The technique that can be used is computational fluid dynamic (CFD) simulation, which uses software to carry out simulations and iterations.

2. Research Methods

This research aims to determine the effect of the AFR on the flow and combustion characteristics in the boiler burner through CFD modeling in ANSYS Fluent 19.1. The combustion process in the burner was tested with AFR variations set to 6.47, 6.79, 7.44, and 8.09. The modeling steps are divided into three stages: pre-processing, processing, and post- processing. The pre-processing stage is the image design and meshing stage. The geometric design using SpaceClaim 19.1 software is shown in Figure 1.

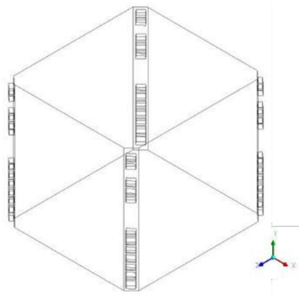


Fig. 1. Burner Tangentially Pulverized Coal Boiler

Meshing is the technique of dividing a domain into smaller areas. This makes the flow domain more discrete and straightforward when applying controlling equations. To obtain an accurate simulation, the choice of meshing for a geometry is made following predictions of changes in flow patterns. There are several nodes in the Burner meshing 409059. Figure 2. is ameshing image for 3D modeling.

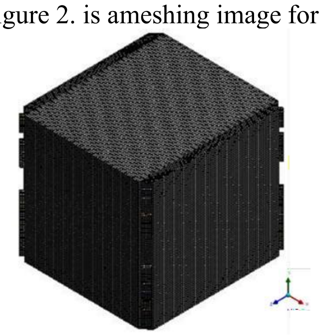


Fig. 2. Meshing Burner Results

The processing stage is carried out using Ansys Fluent 19.1 software, which consists of several stages: model, material, injection, operating conditions, boundary conditions, solution, initialize, and residual. In numerical modeling, the turbulence model uses the k-ε Standard because modeling with fully turbulent flow, discrete phase model for coal particles, and species transport model for chemical reactions in combustion [3][4][8]. The material mix was chosen as coal-hv-volaties-air for Medium Rank Coal (MRC) coal based on the coal analysis used in the performance test.

In post-processing, data collection from simulation results is carried out qualitatively and quantitatively through contours and data presented in graphs. The observation positions are at each injection elevation of Coal and Over Fire Air (OFA).

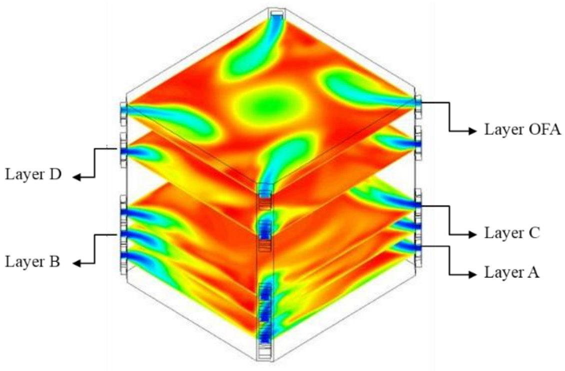


Fig. 3. Location of data collection

3. Research Results and Discussion

3.1 Grid Independence

This study applies a grid to reduce the mesh size and increase accuracy. The grid-independent test was done using three burner meshing models that had numerous nodes: (a) 380092, (b) 409059, and (c) 444666. Validation was carried out on the pressure before the burner outlet with an operating pressure of -85.53 Pa. Comparison of actual pressure values with simulated values is shown in Table 1.

Table 1. Grid independence test

Grid	a	b	c
	380092	409059	444666
Simulation	-87.54	-86.36	-87.24
Actual	-85.53	-85.53	-85.53
% Error	2.35	0.97	2.00

The grid independence test results found that the slightest error value for type b meshing was0.97%, so the grid used in the simulation was type b meshing with 409059 nodes.

3.2 Analysis of Numerical Simulation Results

The investigation was performed by comparing the computational combustion simulation results to the initial AFR configuration. The numerical simulation results will be analyzed for velocity distribution, temperature, O_2, CO_2, and CO.

3.2.1 Velocity Distribution

The flow and combustion pattern is characterized by the formation of a rotating fireball in the burner zone, which is typical for Tangentially Fired boilers. The effect of the fireball is that the trajectory of the coal particles will be longer, so the period of the particles in the furnace area will be more extended [6][11]. In addition, with a fireball, there will be an even distributionof temperature in the waterwall tube.

Velocity distribution at z=center, the tilting angle in this configuration is set according to actual field conditions, namely for coal A in the horizontal direction (0°), coal C in the downward direction (-30°), and for coal D in the downward direction (-20°) so that in Figure 4(a) shows different fireball sizes in coal C and D where the fireball is more significant at a tilt angle of 0°. in the vertical section, the actual configuration conditions have a high velocity reaching 15 m/s, due to the formation of swirls [2].

The flow velocity contour in the burner is needed to analyze the movement of coal particles carried by the combustion air, as shown in Figure 4(b). At the center, the velocity is lower, and at the outside, it is higher, forming a swirl or vortex. As expected, an asymmetrical counterclockwise swirling flow was found at the burner center.

The rotating flow becomes stronger along the burner height from A to C. Then it decreases at elevation D because the distance between the A-C elevation and D is quite far, reducing the push or swirl flow effect from the elevation below, and the air supply is low. At OFA elevation, the velocity again increases because it has a higher air supply.

Figure 4(c) shows the velocity graph taken at the average of each boiler burner elevation. The velocity graph in the four conditions shows that when the AFR increases, which means the combustion air mass flow rate increases, the velocity in the burner will also increase. The lowest velocity is in actual conditions AFR 5.84, with the lowest velocity at elevation A 12.86 m/s and the highest at elevation OFA 16.4 m/s. In comparison, the highest velocity is in AFR conditions8.09, with the lowest velocity at elevation A at 14.5 m/s and the highest at OFA elevation at 19.6 m/s.

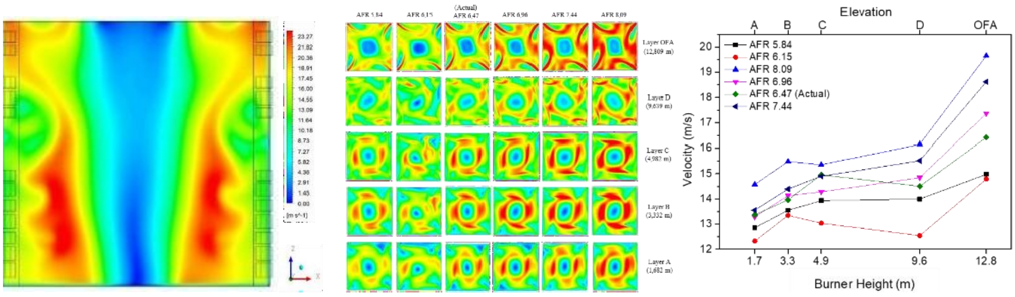


Fig. 4. (a) Velocity contour at z=center of boiler burner (b) Velocity contour at boiler burner elevation (c) Graph of average velocity at boiler burner elevation

3.2.2 Temperature Distribution

The purpose of combustion in the Thermal Power Plant combustion chamber is to convert the chemical energy contained in the fuel into heat to change the phase of the working fluid. Combustion efficiency is often related to the temperature in the combustion chamber. Next are observations on each coal burner elevation and OFA. Observing the elevation of the coal burner can observe how the combustion process occurs between coal and combustion air to produce heat, which can be seen from the temperature distribution. Meanwhile, observationsat OFA were carried out to find out how to reduce the temperature and avoid NOx formation by adjusting the heat requirements in the heat exchanger array and improving combustion by injecting additional air [7][9]. The results of observing temperature contours at each elevation are shown in Figure 5(a).

Overall, the distribution of temperatures at each elevation is the same; that is, the higherthe elevation, the higher the temperature because the mixing conditions of fuel and air are morehomogeneous, so the fuel provided to the lower elevation coal burner is not entirely burned. It will burn at the subsequent burner elevation [5]. The flue gas flow forms a vortex due to the angle formed by the burner inlet. At the center point, the vortex is yellower, indicating that the temperature in this area is lower than the area in the turbulence path. Then, there is a decrease in temperature at the OFA elevation due to the secondary air supply; cold OFA air at a temperature of 700 K causes a reduction in temperature even though it provides additional air for burning char (residual carbon) [2]. If the OFA setting is adjusted, the temperature before entering the heat exchanger line will be lower, thereby reducing the occurrence of overheating.

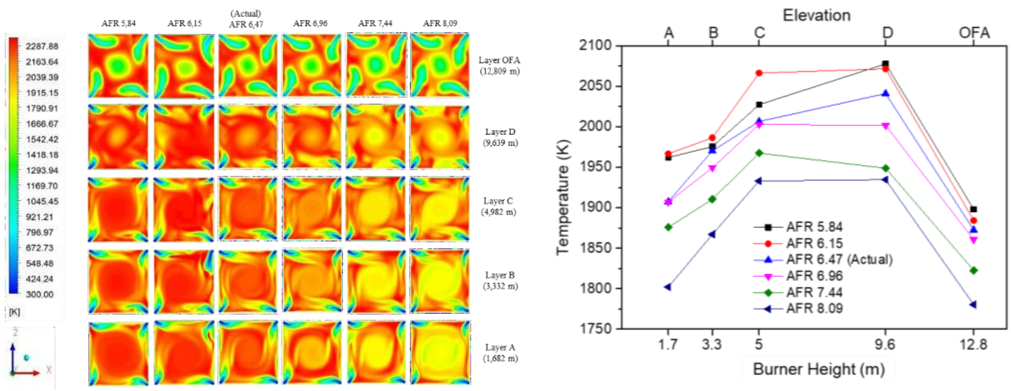


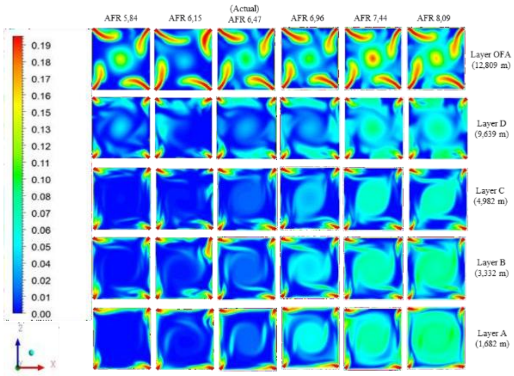
Fig. 5. (a) Temperature contour at boiler burner elevation
(b) Average temperature graph at boiler burner elevation

Quantitative data in the form of temperature values at each elevation in each case is depicted as a graph, as shown in Figure 5(b). From all the simulation cases carried out, the trendline from the graph shows the same trend: when the AFR increases, which means the mass flow rate of combustion air increases, the temperature in the burner will decrease; the cause is that the mass flow rate of combustion air is higher so that the airflow velocity is also higher. This flow velocity makes mixing air and fuel faster, making the combustion process faster. Themixing process is influenced by the burner angle, which forms turbulence. The lowest temperature occurred at AFR 8.09, with the lowest temperature at layer A 1780.5 K and the highest in layer D 1802.2 K, while the highest temperature in AFR conditions is 6.15 with the lowest temperature in layer A 1966.67 K and the highest in layer D 2071.45 K even though it has almost the same value as AFR 5.84. Still, the trend is slightly higher, with an AFR value of 6.15.

3.2.3 Distribution O2

O2 distribution observation is needed to learn more about the complete combustion of char, which is characterized by the smallest number of O_2 mole fractions.

Based on Figure 6(a), in each case, the O2 flue gas contour in the actual conditions at elevations A to D shows that oxygen is almost wholly consumed to oxidize coal particles in the combustion process, shown by the dark blue contour, especially at elevation C, even with the air mass flow rate. The same secondary, but at that point, there is still a char-burning process from elevations A and B, so the secondary air supply for each burner elevation must be considered with the ignition time required for the fuel to burn completely [3].



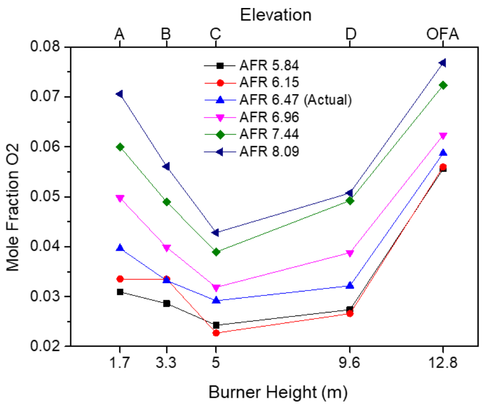


Fig. 6. (a) O_2 mole fraction contour at boiler burner elevation
(b) Average O_2 mole fraction graph atboiler burner elevation

All the simulation cases show that when the AFR is higher, the combustion air mass flow rate is higher, and the O_2 value is higher, which indicates that the combustion is becoming more imperfect. The highest O_2 occurs at AFR 8.09 conditions, with the lowest O_2 at elevation C 0.04 and the highest at elevation A 0.07. In contrast, the lowest O_2 is at AFR 5.84 conditions, with the lowest O_2 at elevation C 0.024 and the highest at elevation A 0.0309; a large amount of air in combustion makes the O_2 value high, which means that the combustion air does not bind withcarbon and this results in heat loss in the flue gas, namely the heat resulting from combustion will be absorbed by the excess air and then carried away by the flue gas so that the heat transferprocess in the boiler heat exchanger is disrupted.

3.2.4 CO_2 Distribution

The combustion process produces exhaust gases, including carbon dioxide (CO2). The composition of the exhaust gas shows complete combustion; the more carbon burned, the greater the CO gas2 formed.

Observations at each elevation aim to find out in more detail the formation of CO_2 exhaust gas, which is a gas that results from burning coal with air. In Figure 7(a), you can see in more detail the formation of CO_2 gas, which occurs starting from the elevation of coal burner A and increasing along with the elevation of the burner. The contour shows the formation of more significant CO_2 with a reddish-orange color. In this condition, the most complete combustion occurs at elevation C. This happens because there is remaining unburned fuel at elevations A and B, which then burns at elevation C. At elevation D, CO_2 flue gas tends to fall because the surrounding air supply is high. At OFA elevation, the CO_2 flue gas mole fraction will decrease because secondary air is not used for combustion but to reduce the flue gas temperature.

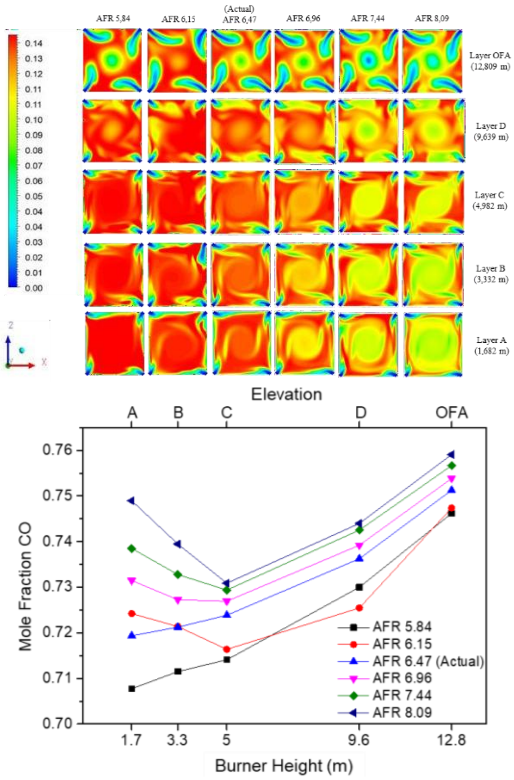


Fig. 7. (a) CO_2 mole fraction contour at boiler burner elevation (b) Average CO_2 mole fraction graph at boiler burner elevation

The graph in Figure 7(b) reveals that the trendline resembles the temperature graph. This is because the mole fraction of CO_2 exhaust gas is directly proportional to temperature. The higher mole fraction of CO_2 flue gas indicates an oxidation process occurs between carbon and O2 at a stoichiometric composition in that area [10]. All the simulation cases carried out show that when the AFR is higher, which means the combustion air mass flow rate is higher, the value is lower, which indicates that the combustion is becoming more imperfect because the combustion rate and combustion efficiency depend on time; every chemical reaction takes time. In some instances, such as in the combustion case, the coal powder must be in the combustion zone in the combustion chamber long enough to burn completely. The lowest CO_2 occurred in AFR 8.09 conditions, with the lowest CO2 at OFA elevation 0.09 and the highest at C elevation 0.11. In comparison, the highest CO2 was in AFR 5.84 conditions, with the lowest CO_2 at OFA elevation 0.107 and the highest at C elevation 0.128.

3.2.5 CO Distribution

When a reaction occurs between the carbon contained in coal and oxygen from the air, or what is also commonly known as the combustion process. But this does not always happen in its entirety. In some situations, such as when the amount of oxygen is insufficient or the contact with the fuel is not optimal, the combustion process will not occur entirely, resulting in carbon monoxide (CO) formation. Even in ideal circumstances, carbon dioxide (CO_2) should be formed.

Observations at each elevation were carried out to determine in more detail the formation of CO gas at each elevation of the coal burner under six conditions of variation in combustion air composition. From Figure 8(a), it can be seen that the formation of CO gas occurs a lot at the lowest elevations, namely elevation A and elevation D. At elevation C, the formation of COis the least, so it can be said that the fuel at elevation C has the least amount of fuel that is not burned.

From the graph in Figure 8(b), The trendline is almost the same in each simulated case:when AFR is higher, which means the mass flowrate of combustion air is higher, the CO Molefraction value is also higher, the highest CO Mole fraction in AFR 8.09 conditions with the lowest CO at elevation C 0.73 and the highest at elevation OFA 0.76. Meanwhile, the lowest CO was in AFR conditions of 5.84, with the lowest CO at elevation C 0.714 and the highest atelevation OFA 0.746. According to the theory, burning with more air prevents the generation of CO, which occurs due to a lack of oxygen during combustion. From this, it can be seen that the optimal combustion process must consider turbulence and time to ensure that the fuel molecules make chemical reactions to oxygen in the air. Too high a SOFA or CCOFA ratio at a fixed OFA ratio quickly increases the unburned carbon due to insufficient mixing between the powerful air jet penetrating deep into the center with the coal particles concentrated near the walls [2].

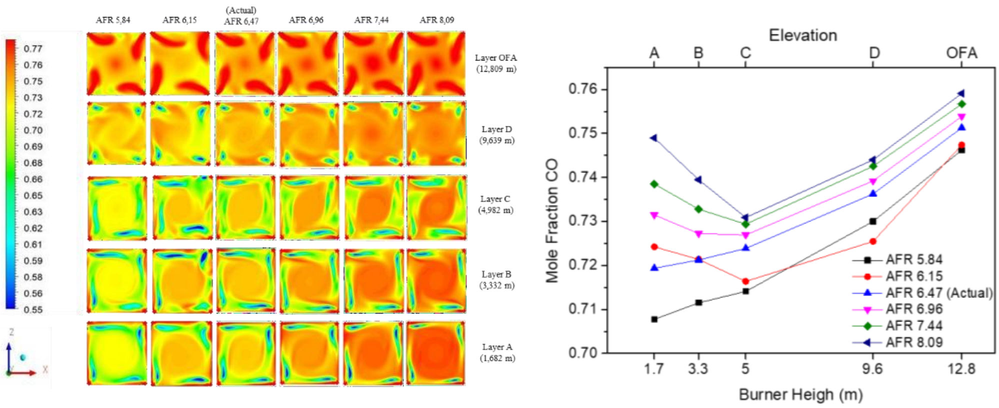


Fig. 8. (a) CO mole fraction contour at boiler burner elevation
(b) Average CO mole fraction graph atboiler burner elevation

4. Conclusion and Suggestions

From the simulation "Numerical Study of the Effect of AFR on Flow and Combustion Characteristics in Tangentially Pulverized-Coal Boiler Burners", the conclusions obtained are:

1. Increasing the AFR by increasing the secondary air value in the combustion process affects the flue gas velocity in the burner; the higher the AFR value, the higher the flue gas velocitywill be.
2. Increasing the AFR by increasing the secondary air value affects the flue gas temperature inthe burner; the higher the AFR value, the lower the flue gas temperature tends to be. The highest temperature was AFR 6.15, followed by AFR 5.84, AFR 6.47, AFR 6.96, AFR 7.44,and AFR 8.09.
3. The O_2 content in flue gas resulting from combustion was lowest at AFR 5.84, followed by AFR 6.15, AFR 6.47, AFR 6.96, AFR 7.44, and AFR 8.09. The AFR 5.84 condition is the best in this case because it has the lowest O2 content. This shows an oxidation process between carbon and O_2 at a more stoichiometric composition.
4. The CO_2 content in flue gas resulting from combustion is highest at AFR 5.84, followed by AFR 6.15, AFR 6.47, AFR 6.96, AFR 7.44, and AFR 8.09. The AFR 5.84 condition is the best in this case because it has the highest CO_2 content. CO is the lowest, indicating an oxidation process between carbon and O_2 at a more stoichiometric composition.
5. From the simulation results of AFR 5.84, which means that a reduction in combustion air from actual conditions is more recommended because it has a higher temperature with the lowest O_2 content, highest CO_2, and lowest CO_2 species components so that the combustion process is getting closer to stoichiometry and unburned carbon is decreasing.
6. A too-high or too-low air ratio quickly increases unburned carbon due to the inefficient mixing of air and coal particles.

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