CFD Analysis on Stoker Boiler Cofiring Sugarcane Bagasse Biomass

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Abstract - **Biomass cofiring has emerged as a promising approach to reducing greenhouse gas emissions from coal-fired power plants. This study employs Computational Fluid Dynamics (CFD) to analyze the thermal and emission performance of cofiring coal with sugarcane bagasse in a stoker-type boiler. Simulations were conducted using ANSYS Fluent to evaluate combustion characteristics at sugarcane bagasse biomass percentages of 0%, 35%, and 70%. The results show that increasing the proportion of bagasse reduces furnace temperature and CO_2 emissions, attributed to the biomass's lower carbon and higher oxygen content. Specifically, the average furnace temperature drops from 963.94 K to 862.47 K. Correspondingly, CO_2 emissions decrease due to the lower carbon content of bagasse, while the mass fraction of O_2 in the flue gas increases, reflecting reduced demand for excess air. These findings support the viability of sugarcane bagasse as a co-firing fuel to enhance combustion sustainability and minimize environmental impact.**

Keywords: Biomass cofiring, Sugarcane bagasse, Computational Fluid Dynamics, CFD, Coal combustion, Emission reduction, CO_2 emissions, O_2 mass fraction, Stoker boiler, Renewable energy.

I. INTRODUCTION

Renewable energy has become a key tore solving the world's energy challenge and the growing climate change concerns. The world's dependence on fossil fuels, such as coal, oil, and natural gas, has led to a significant increase in air pollution and greenhouse gas emissions, contributing to global warming and environmental degradation [1]. The combustion of fossil fuels releases significant emission quantities of carbon dioxide (CO_2), sulfur dioxide (SO_2), nitrogen oxides (NO_x), and particulate matter (PM), which all contribute to climate change and environmental degradation [2]. According to the International Energy Agency (IEA), power plants accounted for approximately 40% of global CO_2 emissions in 2021, with coal-fired power stations being the primary contributors.

The environmental impact of power plant emissions has been extensively studied. A comprehensive assessment of coal-based electricity generation in China found that in 2014, the power sector released approximately 3.44 billion tons of CO_2, 8.56 million tons of NO_x, and 11.9 million tons of SO_2 [3].

Cofiring generally involves applying biomass fuel as a renewable energy. Cofiring biomass is a cost-effective method of producing environmentally friendly energy [4]. Co-firing has been widely adopted as an interim strategy to reduce CO_2 and NO_x emissions, reaching a reduction of 65% and 50% [5]. Differences in biomass's chemical properties impact combustion performance and emissions. Biomass has a high amount of oxygen, hydrogen, and volatile matter, which improves reactivity and ignition characteristics compared with coal [6]. The analysis is essential for understanding how solid fuel behaves during combustion.

Sugarcane bagasse has emerged as a promising renewable fuel due to its high availability, low cost, and carbon-neutral properties. Sugarcane bagasse exhibits high volatile matter content (68-85%) and low sulfur content (0-0.39%), which contributes to cleaner combustion with reduced sulfur dioxide (SO_2) emissions. However, bagasse also presents challenges due to its high moisture content (45–55% in raw form) and relatively low energy density compared to coal [7]. Sugarcane bagasse combustion thermal efficiency has been identified amount 33.7–41% and reduced NOx and SO_2 emissions [8].

Computational Fluid Dynamics (CFD) has become a powerful approach to simulate and analyze combustion behaviours, fuel mixing, pollutant generation, and heat transfer dynamics [9]. CFD modelling provides detailed insights into the physical and chemical interactions within combustion chambers, aiding in the optimization of operational parameters to enhance performance and minimize environmental impacts [10]. Despite its advantages, CFD-based co-firing analysis remains computationally intensive, requiring high-performance computing resources and experimental validation. Continuous advancements in

computational power and machine learning integration are expected to improve the accuracy and applicability of CFD in optimizing sustainable combustion technologies. This paper explores the role of CFD in optimizing biomass co-firing, focusing on temperature performance, pressure, and emissions.

II. RESEARCH METHODOLOGY

2.1 Geometry and Mesh Generation

In this paper, a stocker-type boiler was modeled using SolidWorks software and simulated using Ansys Fluent 2023 R2. Figure 1 shows the stocker boiler's structure design and boundary conditions (1) coal inlet, (2) air inlet, and (3) outlet. The detailed specification of the stocker boiler can be seen in Table 1.

Table 1: Dimension of Boiler

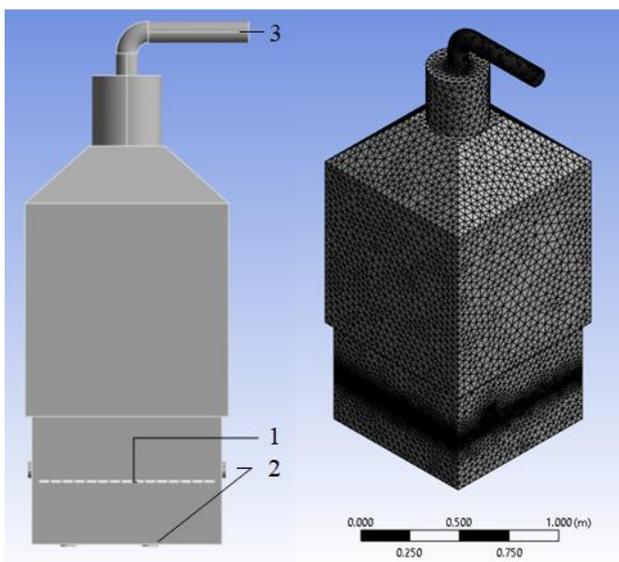| Parameter	Description
length	0.95 m
Width	0.95 m
Height	2.45 m
Dimensions of the bed	0.05 m
Number of beds	15
Air inlet diameter	0.07 m
Outlet diameter	0.1 m

Figure 1: Geometry of Boiler

The model stocker boiler was meshed automatically using ANSYS Fluent and the sizing method. The number of cells is approximately 1812605, and the skewness is 0.23118. The meshing result can be seen in the figure.

2.2 Numerical Method

The simulation was performed using ANSYS Fluent 2023 R2 to model the cofiring of coal and sugarcane bagasse biomass. The k-εrealizable turbulence model with steady-state situations is used in this simulation to analyze regions that are not near walls with constant conditions [11]. The fluid blends several chemicals in the stoker boiler furnace, including combustion products and combustible substances. Activate the Species Transport-Eddy Dissipation model for comprehensive mechanisms of chemical reactions in turbulent reactions [12]. Table 2 shows the material properties of coal and sugarcane bagasse injected from the bed. The trajectory of coal and sugarcane bagasse biomass particles from the top-side combustion bed is traced using the Discrete Phase Model (DPM) technique.

Table 2: Properties of Sugarcane Bagasse and Coal

Content	Sugarcane Bagasse (%)	Coal (%)
Ultimate Analysis		
Carbon	44.1	76.242
Nitrogen	0.36	1.723
Sulfur	0.19	1.454
Oxygen	49.39	10.884
Hydrogen	5.96	9.698
Proximate Analysis		
Volatile M	74.87	47.94
Fixed Carbon	14.93	35.61
Moisture	5.8	5.85
Ash	4.40	10.6
Calorific value	1.73×10^4 kj/kg	2.89×10^4 kj/kg

2.3 Governing Equation

The Eulerian approach is widely employed to capture the comprehensive behavior depiction of the complex interactions occurring during cofiring. The equation displays mass conservation, momentum, and energy for a multiphase system with species transport, as present in Equations 1-6.

Mass conservation:

$$\frac{\partial}{\partial t}\left(\alpha_q \rho_q\right) + \nabla \cdot \left(a_q \rho_q \vec{v}_q\right) = 0 \tag{1}$$

Momentum conservation:

$$\frac{\partial}{\partial t}\left(\alpha_q \rho_q \vec{v}_q\right) + \nabla \cdot \left(a_q \rho_q \vec{v}_q \vec{v}_q\right) = -a_q \nabla p + \nabla \cdot \overline{\overline{\tau}} + a_q \rho_q \vec{g} + K_{pq}\left(\vec{v}_q - \vec{v}_p\right) \tag{2}$$

Energy conservation:

$$\frac{\partial}{\partial t}\left(\alpha_q \rho_q h_q\right) + \nabla \cdot \left(a_q \rho_q \vec{v}_q h_q\right) = a_q \frac{\partial p_q}{\partial t} + \overline{\overline{\tau}}_q \div \nabla \vec{v}_q - \nabla \cdot \vec{q}_q \tag{3}$$

Turbulence Model:

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_j}(\rho k u_j) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right] + G_k + G_b - \rho\varepsilon - Y_M + S_k \qquad (4)$$

$$\frac{\partial}{\partial t}(\rho\varepsilon) + \frac{\partial}{\partial x_j}(\rho\varepsilon u_j) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial\varepsilon}{\partial\varepsilon_j}\right] + \rho C_1 S\varepsilon - \rho C_2 \frac{\varepsilon^2}{k + \sqrt{v\varepsilon}} + C_{1\varepsilon}\frac{\varepsilon}{k}C_{3\varepsilon}G_b + S_\varepsilon \qquad (5)$$

Where:

$$C_1 = max\left[0.43, \frac{\eta}{\eta+5}\right], \eta = S\frac{k}{\varepsilon}, S = \sqrt{2S_{ij}S_{ij}} \qquad (6)$$

The boundary conditions for this simulation were defined using ANSYS Fluent 2023 R2. The analysis was performed as an internal flow simulation to evaluate the outlet's temperature distribution and the mass fractions of CO_2 and O_2. The primary air inlet was specified at a mass flow rate of 0.1 kg/s, the secondary air inlet at 0.001 kg/s, and the coal feed inlet at 0.0055 kg/s.

2.4 Mesh Independent Test

To guarantee that the numerical results are not affected by the number of meshing and to minimize simulation time. The mesh-independent testis an essential stage that needs to be concluded. Figure 2 shows the number of mesh compared to temperature. Five mesh numbers were tested from 1812605 to 1877147. The result shows that the simulation mesh numbers 1812605 have no significant changes observed in the temperature parameter. The number of mesh 1812605 was chosen to run in this simulation.
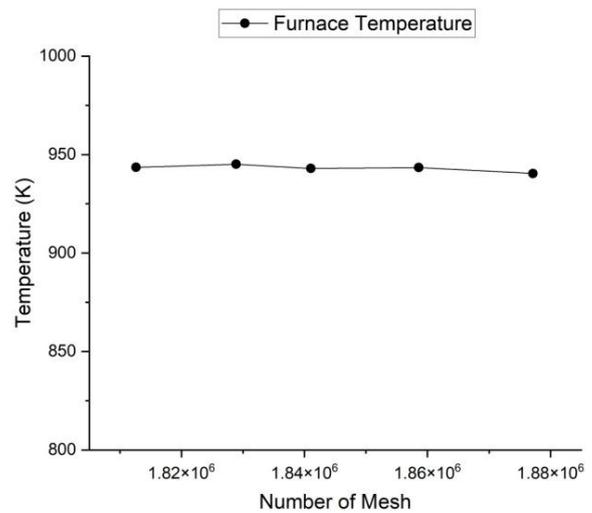

Figure 2: Mesh Independent

2.5 Validation Data

The reference of this simulation is used from an experiment data boiler stocker conducted by the Department of Mechanical Engineering, Diponegoro University Boiler Stocker in the Department of Mechanical Engineering at Diponegoro University. The furnace temperature and the mass fraction of CO_2 are among the validated parameters. Table 3presents detailed data validation.The error value for each validation data set in the table is less than 10%.The data shows that the allowance limit is below 10% [13].

Table 3: Validation Data

Parameter	Experimental Data	Simulation Data	Error Data
Temperature (K)	940.8	943.5	0.3%
CO_2(%)	5.1	5.4	5.8%

III. RESULTS AND DISCUSSIONS

3.1 Furnace Temperature

Furnace temperatures are observed with percentages of sugarcane bagasse biomass, 0% or 100% of coal, 35%, and 70%. The result is shown in Figure 3. The results of the simulation show that the distribution of gas temperatures varies. The average temperature is low near the bottom and higher at the bed boiler. The primary furnace zone is between 0.6 and 1.6 meters, and at 100% coal condition, the highest average temperature in the furnace reference is963.94 K. When sugarcane bagasse is burned at a percentage of 35% and 75%, the temperature decreases to an average temperature at the height reference, reaching 912.78 K and 862.47 K. The decreasing temperature occurs when the percentage of sugarcane bagasse increases, as shown in Figure 4. The factor affecting the temperature decrease is that coal has a higher carbon content than sugarcane bagasse biomass. Furthermore, sugarcane bagasse has high volatile matter. A high volatile matter content leads to earlier devotalization during the combustion process, potentially shifting the combustion zone. As a result, the boiler's average temperature drops, and heat is distributed unevenly [14].
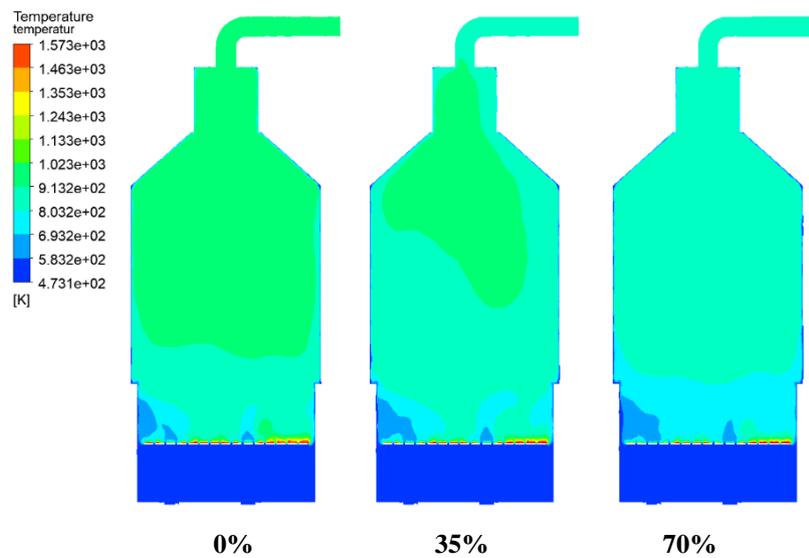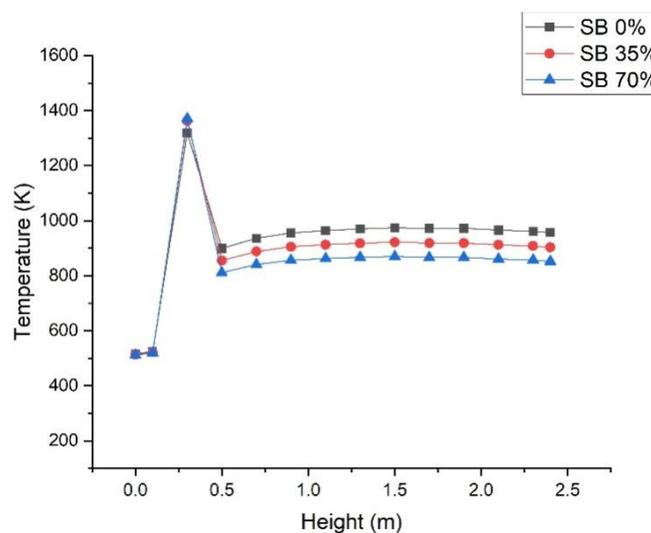
Figure 3: Furnace Temperature

Figure 4: The average temperature along the furnace height

3.2 CO_2 Gas Emission and O_2

Figure 5 shows the distribution of CO_2 mass fraction. At 0% cofiring sugarcane bagasse biomass or 100% of coal, the mass fraction of CO_2 is 7.99×10^{-2}; when the percentage is 35% and 70% cofiring sugarcane bagasse biomass, the mass fraction of CO_2 drops to 7.19×10^{-2} and 7×10^{-2}. The sugarcane bagasse contains less carbon than coal. Therefore, the less carbon that can be oxidized to CO_2, the more biomass is consumed. This indicates that the combustion process generates less CO_2. Further, the sugarcane bagasse has high oxygen content, which makes the combustion reaction rapid. Intrinsic oxygen within the fuel reduces the necessity for additional combustion air. This reduction limits the generation of incomplete combustion byproducts, such as carbon monoxide CO, thereby promoting further oxidation to carbon dioxide CO_2.

Oxygen (O_2) in boiler exhaust gases originates from excess combustion air supplied to ensure complete fuel oxidation. During the combustion process, air is introduced into the chamber to facilitate efficient combustion; however, when provided in excess, a portion of the oxygen does not react and remains as free O_2 in the flue gas. This unreacted oxygen is emitted alongside other combustion byproducts. The level of O_2 in the exhaust stream is a critical parameter for assessing combustion efficiency and the environmental sustainability of the boiler system. The distribution of O_2 mass fraction in the boiler stoker can be seen in Figure 6.
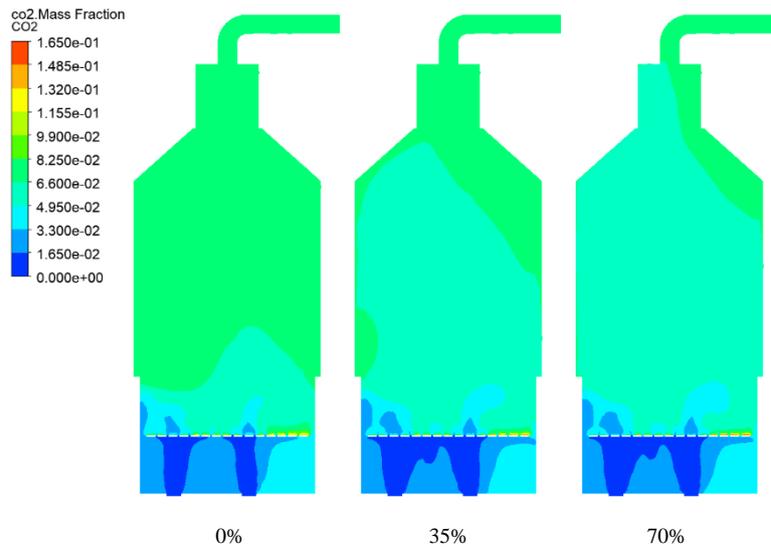
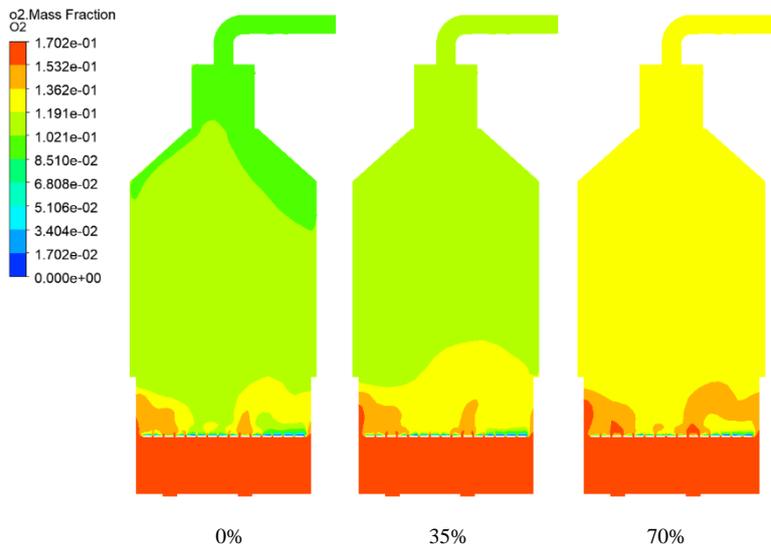**Figure 5: CO$_2$ mass fraction contour in different percentages**

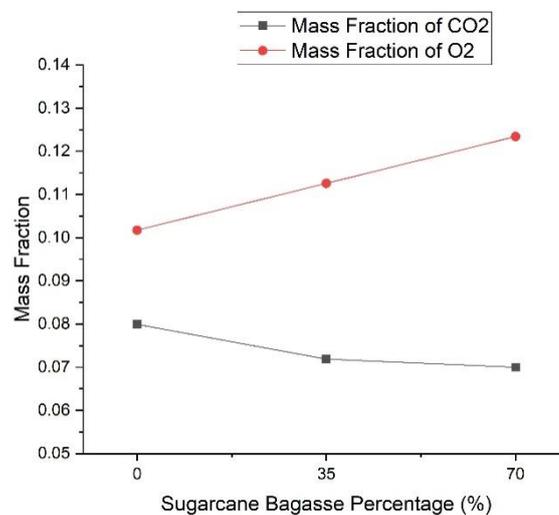**Figure 6: O$_2$ mass fraction contour in different percentages**

Figure 7: CO$_2$ and O$_2$ mass fraction of cofiring sugarcane bagasse in the outlet

The O_2 mass fraction in cofiring boiler stoker increases for sugarcane bagasse percentages of 0%, 35%, and 70% by 1.02×10^{-1}, 1.13×10^{-1}, and 1.23×10^{-1}. Figure 7 shows that O_2 emissions at the boiler outlet increase with a higher ratio of bagasse biomass in the fuel mixture. An increase in the O_2 mass fraction within the stoker boiler furnace suggests a decreasing proportion of oxygen from the primary and secondary air streams actively participating in the combustion reaction. On the other hand, sugarcane bagasse biomass already has a high oxygen content. Consequently, some of the oxygen that fails to react with carbon to produce CO_2 remains in the flue gas as unreacted O_2, a condition that becomes more pronounced with a higher ratio of bagasse in the fuel blend [15].

IV. CONCLUSION

An analysis of numerical simulations was undertaken on boiler stoker cofiring sugarcane bagasse biomass percentages of 0%, 35%, and 70%.From the result, the conclusions can be drawn as follows:

1. The furnace temperature continuously decreases as the sugarcane bagasse biomass percentage ratio increases. When the biomass percentage ratio increases from 0 to 70%, the average temperature in the primary combustion zone decreases from 963.94 K to 862.47 K.
2. Cofiring sugarcane bagasse with coal reduces CO_2 emissions due to the bagasse's lower carbon and higher oxygen content. As the bagasse ratio increases, the CO_2 mass fraction decreases while the unreacted O_2 in the flue gas rises.

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