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RESEARCH ARTICLE

Performance Analysis of Fluidized Bed Gasifier Using Computational Fluid Dynamics: The Impact of Particle Size and Air Preheating on Gas Composition

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ABSTRACT: Gasification is an efficient process that converts organic and fossil fuel-based carbonaceous materials into valuable gases such as carbon monoxide, carbon dioxide, and hydrogen, which can be used as fuel. This study aims to enhance the efficiency of the gasification process by utilizing a Computational Fluid Dynamics (CFD) model to simulate a Fluidized Bed Gasifier (FBG) system. Sawdust serves as the fuel, while sand particles form the fuel bed. The model, developed using the Eulerian-Eulerian approach, explores the effects of air preheating and variations in particle size on the composition of producer gas. By analyzing particle sizes of 0.5 mm and 1 mm at preheating temperatures of 400 K and 600 K and a velocity of 1 m/s, the study reveals significant variations in gas composition. At 400 K, the mole fraction and mass fraction of fuel gases such as CO and H_2 increase for larger particle sizes, reaching peak performance for 1 mm particles. The performance of the gasifier improved by 75% at 400 K for 1 mm particles. However, when the temperature was increased to 600 K, CO was converted to CO_2, demonstrating that higher temperatures lead to increased combustion of fuel gases. This study offers valuable insights into optimizing gasification processes for enhanced energy efficiency and gas yield in fluidized bed systems.

Keywords: Gasification, Sawdust, Fluidized Bed Gasifier, Computational Fluid Dynamics, Eulerian-Eulerian approach.

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1. INTRODUCTION

Biomass, a renewable source of energy derived from plant and animal materials, offers significant potential for sustainable energy production [1]. As concerns over climate change and depleting fossil fuel reserves grow, the need for cleaner and more efficient energy sources has intensified. Biomass can be converted into biofuels through various processes, such as catalytic reactions, fermentation, combustion, digestion, and pyrolysis, making it a versatile feedstock for energy generation [2]. The primary fuels derived from biomass can be used in several applications, including electricity generation, transportation, and heating. Biomass combustion, in particular, involves complex heterogeneous and homogeneous reactions that release heat and gases suitable for energy production [1-4].

One of the most promising technologies for harnessing energy from biomass is gasification, a process that converts biomass into a valuable gas mixture known as syngas. Syngas primarily consists of carbon monoxide (CO), hydrogen (H_2), carbon dioxide (CO_2), methane (CH_4), and trace amounts of other gases [4, 5]. The composition of syngas is highly dependent on the conditions of the gasification process, such as temperature, pressure, and the biomass feedstock used. Gasification differs from combustion in that it only partially oxidizes the carbon in biomass, producing CO and H_2 rather

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than fully oxidized CO_2. For example, during biomass combustion, carbon reacts with oxygen to form CO_2, while in gasification, the carbon forms CO. Similarly, water is a product of combustion in the form of H_2O, while gasification splits water into H_2 and oxygen. Nitrogen-based compounds, such as nitrogen oxides (NO and NO_2), are typical byproducts of combustion, while gasification produces hydrogen cyanide (HCN), ammonia (NH_3), or nitrogen gas (N_2). Sulfur-containing species in biomass are released as sulfur dioxide (SO_2) or sulfur trioxide (SO_3) during combustion, while gasification forms hydrogen sulfide (H_2S) [6-9].

The modeling of gasification processes often employs the Eulerian-Eulerian approach, which is highly suitable for systems like bubble columns and fluidized bed reactors [1-3]. In this approach, both the gas and solid phases are treated as continuous media, allowing for detailed analysis of complex gas-solid interactions within the reactor. This method is preferred over the more computationally intensive Eulerian-Lagrangian approach, where individual particles must be tracked in the system [2]. The Eulerian-Eulerian method has been instrumental in providing insights into gas flow patterns, temperature profiles, and syngas composition in various gasification systems [3]. Additionally, the performance of fluidized bed gasifiers (FBGs) is influenced by several factors, including air velocity and the equivalence ratio, which is the ratio of oxygen to fuel. Increasing air velocity improves gas quality by enhancing the mixing of reactants, which in turn increases the concentration of H_2 in the syngas [4]. Steam temperature also plays a crucial role in gasification efficiency; higher temperatures favor the formation of CO and H_2, while reducing the production of CO_2 and CH_4 [5].

The relationship between gasification temperature and carbon conversion efficiency has been well-documented. A study by Jones et al. demonstrated that carbon conversion efficiency increases with rising temperature, reaching a peak at 82% at 850°C, compared to 62% at 650°C [6]. However, the optimal steam-to-biomass ratio must be carefully managed, as excessive steam can reduce conversion efficiency at higher temperatures [6]. Their results showed that the highest carbon conversion was achieved at a steam-to-biomass ratio of 7.14 at 850°C, compared to 2.86 at 650°C, emphasizing the importance of optimizing process parameters for maximum efficiency.

Computational fluid dynamics (CFD) has become an invaluable tool for analyzing gasification processes, providing detailed visualizations of gas flow patterns, temperature distributions, and syngas concentrations within reactors [7]. For example, the increase in equivalence ratio leads to greater air mass within the bed during gasification, thereby enhancing the oxidation phase reactions and increasing CO_2 and NO_2 concentrations in the syngas. Additionally, increased moisture content in the feedstock triggers water-gas shift reactions, which convert CO into CO_2 and generate H_2 [8-11]. Chalermsinsuwan et al. conducted a CFD study of fluidized bed reactors using different riser geometries, such as tapered-out risers, standard risers, and tapered-in risers [10]. Their results indicated that tapered-out risers enhanced particle mixing and residence time, leading to more uniform temperature distributions and better overall system performance [8].

Further advancements in gasification technology include multi-stage gasifiers, which have been shown to significantly improve performance. Gomez-Barea et al. developed a three-stage fluidized bed gasifier (FBG) that utilized temperature management, steam addition, and air staging to optimize char and tar conversion [12]. Their system achieved a gasification efficiency of 81%, with a char conversion rate of 98% and a tar content of only 0.01 g/Nm³. In comparison, single-stage FBGs typically exhibit lower efficiencies, with char conversion rates of around 59% and much higher tar content of 31 g/Nm³ [12]. These findings underscore the potential for multi-stage systems to enhance biomass gasification performance.

In this study, we present a comprehensive analysis of fluidized bed gasification, focusing on the optimization of operational parameters, including air velocity, equivalence ratio, steam temperature, and steam-to-biomass ratio. Additionally, we utilize CFD modeling to investigate gas flow patterns, temperature distributions, and syngas composition in fluidized bed gasifiers. The effects of different riser geometries and the implementation of multi-stage gasifiers are also discussed, with a focus on improving gasification efficiency and reducing emissions. Our findings contribute to the ongoing development of more efficient and cleaner biomass gasification technologies.

2. MATHEMATICAL MODELLING

The mathematical modelling involves the representation of physical quantity in primary and secondary phases of solid, liquid and gas. The conservation of mass, momentum and energy are applied to the primary phase and the secondary phase to determine the transfer of the parameters [4].

2.1 Conservation of mass:

The general continuity equation is given as:

$$\frac{\delta}{\delta t}\left(\alpha_q \rho_q\right) + \nabla.\left(\alpha_q\ \rho_q \vec{V}_q\right) = \sum_{p=1}^{n}\left(\dot{m}_{pq} - \dot{m}_{qp}\right) + S_q \quad (1)$$

Continuity equation of gas phase:

$$\frac{\partial t}{\partial t}\left(\alpha_g \rho_g\right) + \nabla\ .\left(\alpha_g \rho_g V_g\right) = 00 \quad (2)$$

Continuity equation of solid phase:

$$\frac{\partial}{\partial t}\left(\alpha_s \rho_s\right) + \nabla\ .\left(\alpha_s \rho_s V_s\right) = 0 \quad (3)$$

2.2 Conservation of momentum:

$$\frac{\partial}{\partial t}\left(\alpha_q\rho_q\vec{V}_q\right)+\nabla.\left(\alpha_q\rho_q\vec{V}_q\vec{V}_q\right)=-\alpha_q\nabla.p+\nabla.\bar{\bar{\tau}}_q+\alpha_q\rho_q\vec{g}+\sum_{p=1}^{n}(\vec{R}_{pq}+\dot{m}_{pq}\vec{V}_{pq}-\dot{m}_{qp}\vec{V}_{qp})+(\vec{F}_q+\vec{F}_{lift,q}+\vec{F}_{vm,q}) \quad (4)$$

Momentum equation for the gas phase:

$$\frac{\partial}{\partial t}(\alpha_g\rho_g\vec{V}_g)+\nabla.(\alpha_g\rho_g\vec{V}_g\vec{V}_g)=-\alpha_g\nabla.p+\nabla.\bar{\bar{\tau}}_g+\alpha_g\rho_g\vec{g}+\mathrm{Ksl}\,(\vec{V}_g-\vec{V}_s \quad (5)$$

Momentum equation for the solid phase:

$$\frac{\partial}{\partial t}(\alpha_s\rho_s\vec{V})_s+\nabla.(\alpha_s\rho_s\vec{V}_s\vec{V}_s)=-\alpha_s\nabla.p+\nabla.\bar{\bar{\tau}}_s+\alpha_s\rho_s\vec{g}+\mathrm{Ksl}\,(\vec{V}_g-\vec{V}_s) \quad (6)$$

2.3 Conservation of energy equation:

The conservation of energy equation for Eulerian multiphase applications, we consider equation of enthalpy and it is given by:

$$\frac{\partial}{\partial t}(\alpha_q\rho_q\vec{V}_q)+\nabla.\left(\alpha_q\rho_q\vec{u}_q\vec{h}_q\right)=\alpha_q\frac{\partial p_q}{\partial t}+\bar{\bar{\tau}}:\nabla\vec{u}_q-\nabla\vec{q}_q+s_q+\sum_{P=1}^{n}(Q_{pq}+\dot{m}_{pq}h_{pq}-\dot{m}_{qp}h_{pq}) \quad (7)$$

3. Geometrical Modelling of Fluidized Bed Gasifier (FBG)

The design and geometry of the Fluidized Bed Gasifier (FBG) are essential for optimizing its performance during gasification. In Computational Fluid Dynamics (CFD) simulations, parameters like temperature, pressure, and velocity are assigned to specific nodes within the grid. The accuracy of the CFD solution increases with the refinement of the grid and the number of cells used in the model, providing more precise results regarding fluid flow and reaction kinetics within the gasifier [4].

For this study, a specific FBG model was designed with a diameter of 0.15 meters and a total length of 1.5 meters. The fuel used is sawdust, a type of biomass, supported by a fuel bed composed of sand. The fuel bed has a length of 0.22 meters, and the entire gasifier extends to a height of 4 meters to provide ample space for the gasification reactions to take place. This extended length ensures that the biomass particles have sufficient time to interact with the air or steam, resulting in efficient conversion into syngas.

The model incorporates detailed material properties. The fuel bed, made of sand, has a density of 1800 kg/m³ and a particle diameter of 0.4 mm. The initial volume fraction of the sand is set to 0.6, indicating that 60% of the fuel bed volume is occupied by solid particles. The sawdust, which serves as the fuel, has a density of 896 kg/m³, and two particle sizes are considered: 0.5 mm and 1 mm. This variation in particle size allows for a more nuanced analysis of how different particle diameters affect gasification efficiency and reaction dynamics.

Several boundary conditions are established for the model. The inlet velocity is set at 0.5 m/s, controlling the rate of gas flow into the system, which in turn affects the fluidization of the bed. The time step for the CFD simulation is 0.001 seconds, and 20 iterations are performed for each time step to capture the transient behavior of gas-solid interactions. The restitution coefficient is 0.9, meaning that particle collisions are relatively elastic, retaining most of their kinetic energy and promoting better mixing within the bed.

The geometric layout of the FBG, shown in Figure 1 (a), offers insight into the arrangement of the fuel bed and fuel particles, as well as the overall gasifier structure. This configuration is crucial for understanding the behavior of gas flows and reaction mechanisms during the gasification process.

4. Computational Model

The computational model used for simulating the FBG involves a mesh consisting of quadrilateral elements with a 5 mm element size (Figure 1 (b), and (c)). This mesh divides the gasifier into small, discrete regions where the physical properties of the system—such as temperature, pressure, and velocity—are calculated. The model includes 1330 nodes and 1214 elements, providing adequate detail for analyzing the behavior of gas flow, heat transfer, and chemical reactions during gasification (Table 1).

By employing a mesh with these specifications, the

CFD simulations effectively capture the essential dynamics of the gasifier, offering a detailed understanding of the fluid flow, temperature distribution, and reaction kinetics within the system.

Table 1. Element Details of the Computational Model.

Element Details	
Element Type	Quadrilateral element
Size of the Element	5 mm
Number of Nodes	1330
Number of Elements	1214

5. RESULTS AND DISCUSSION

In this study, the effects of particle size and air velocity on the gasification process, particularly the production of CO and H_2, were analyzed at three different temperatures: 400 K, 600 K, and 800 K. Using Computational Fluid Dynamics (CFD), contour plots of velocity, pressure, temperature, and turbulent kinetic energy were generated to explore the key parameters affecting syngas composition, specifically focusing on CO and H_2 gas productivity. The two cases investigated involve different sawdust particle sizes and air velocities.

Case-1

- **Sand Particle Size**: 0.4 mm
- **Sawdust Size**: 0.5 mm
- **Air Velocity**: 0.5 m/s
- **Temperature**: 400 K, 600 K, 800 K

Case-2

- **Sand Particle Size**: 0.4 mm
- **Sawdust Size**: 1 mm
- **Air Velocity**: 1 m/s
- **Temperature**: 400 K, 600 K, 800 K

5.1. Effect of Preheating of Air and Particle Size on CO Production

The mass and mole fractions of carbon monoxide (CO) for both cases, across the temperatures of 400 K, 600 K, and 800 K, are shown in Figure 2. The analysis shows that, at lower temperatures, the mass fraction of CO is higher, especially in Case-2 (1 mm sawdust particle size and 1 m/s air velocity) compared to Case-1 (0.5 mm sawdust particle size and 0.5 m/s air velocity). At 400 K, the mass fraction of CO for Case-2 is approximately 75% higher than Case-1, indicating that larger biomass particles and higher velocities result in more CO production at this temperature.

At higher temperatures (600 K and 800 K), the CO production decreases as part of the sawdust undergoes complete combustion. This trend is particularly noticeable in Case-2, where the sawdust particles are larger. The higher velocity in Case-2 results in more rapid combustion, which reduces the CO mass fraction as the sawdust is more completely oxidized, potentially producing CO_2 instead (Figure 3 (a)).

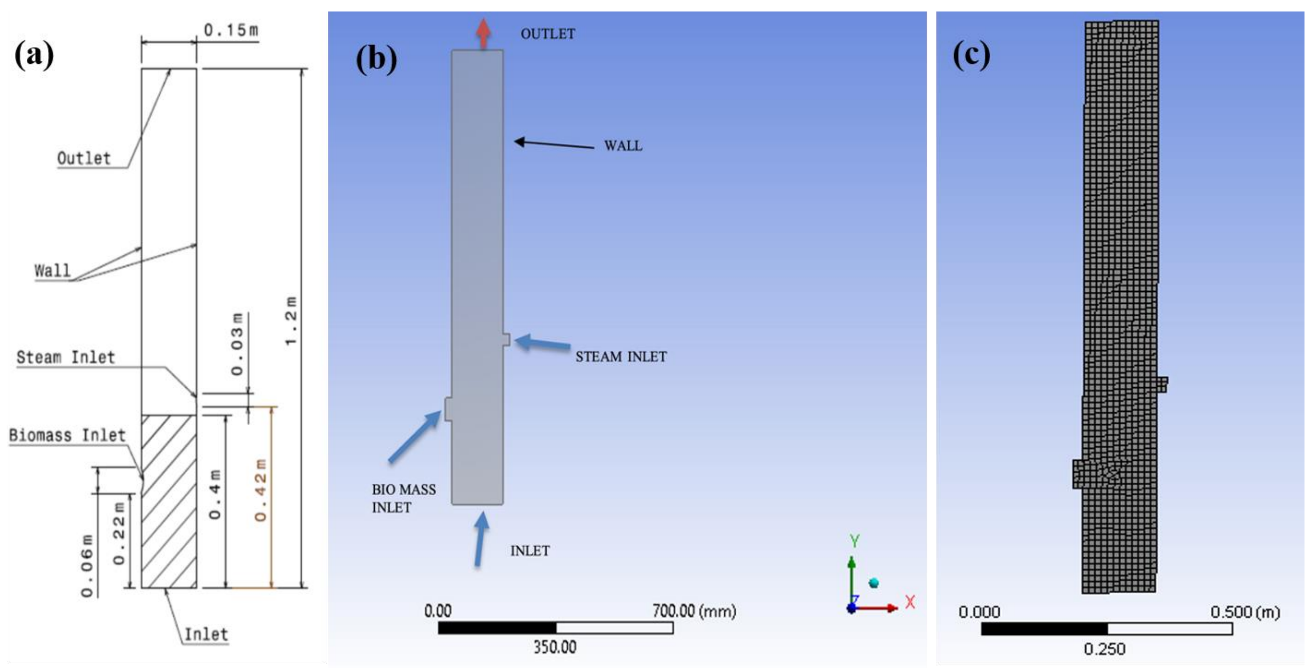

Fig. 1. (a) Geometry, and (b, c) Computational of Fluidized Bed Gasifier (FBG).

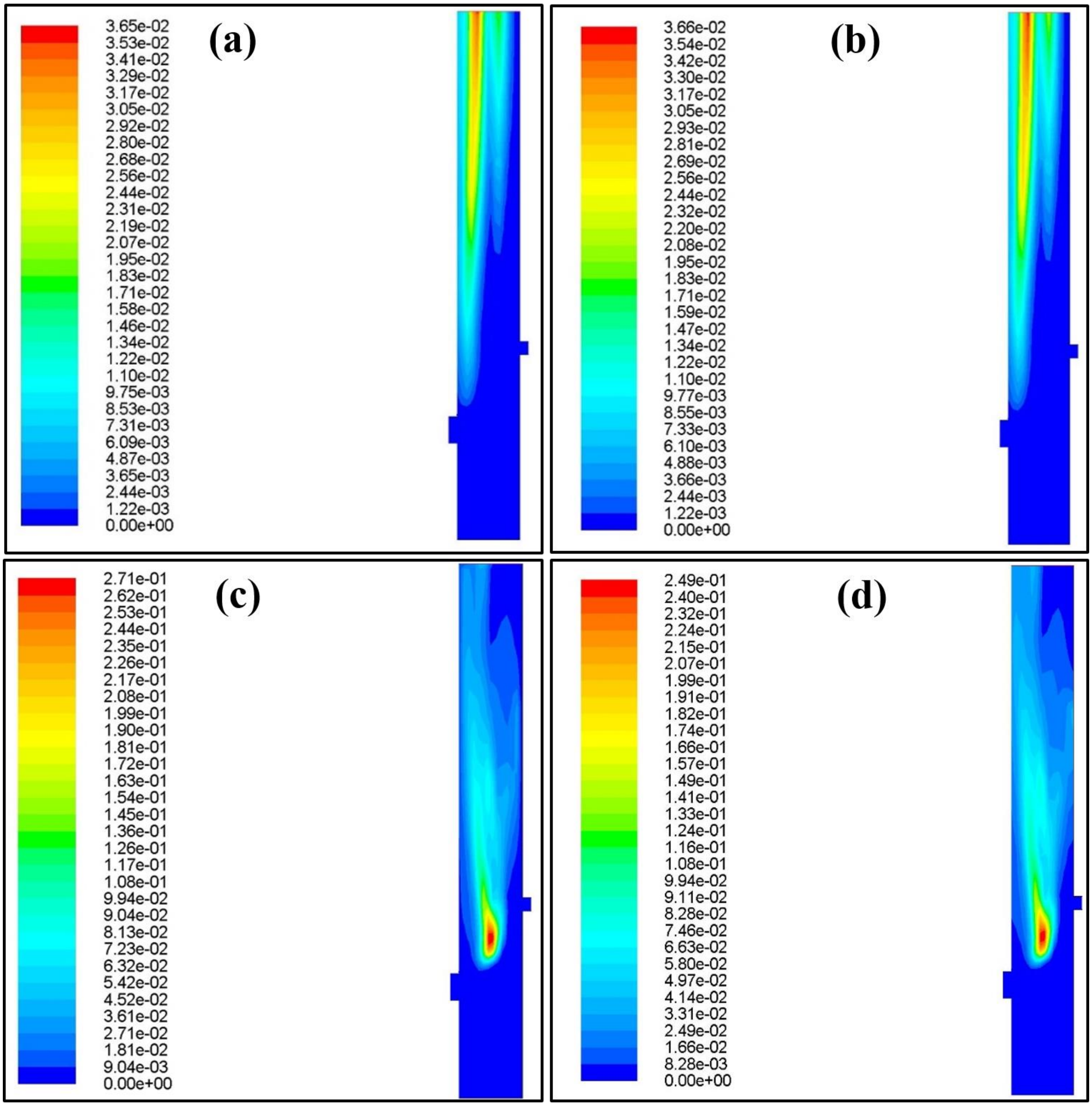

Fig. 2. Contour plot of mass fraction of CO (a and c) for Case-1, and (b and d) for Case-2 at 400K.

The variation in the mole fraction of CO follows a similar pattern to the mass fraction, with the highest concentration of CO occurring at 400 K and decreasing as the temperature rises [13]. At 300 K (preheating phase), the CO content in Case-2 is significantly higher than in Case-1, but at 800 K, this difference diminishes due to the increased likelihood of complete combustion (Figure 3 (b)).

5.2. Effect of Preheating of Air and Particle Size on H_2 Production

The production of hydrogen gas (H_2) is also highly influenced by particle size, air velocity, and temperature. Figure 4 shows the contour plots of H_2 mass fractions for both cases at 400 K. In Case-1, with a 0.5 mm sawdust particle size, the highest concentration of H_2 is found near the inlet region of the biomass, with the gas following along the walls of the gasifier.

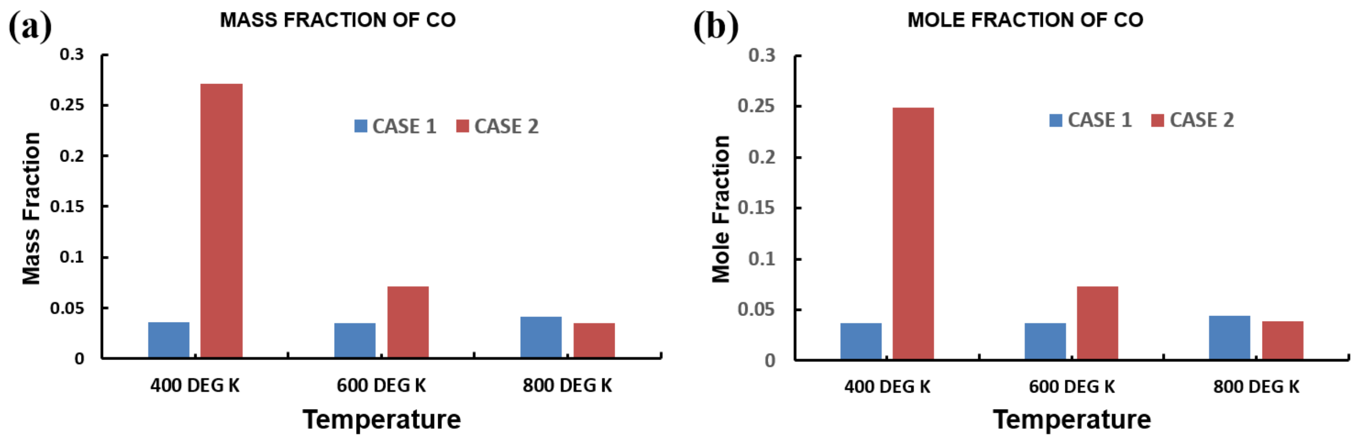

Fig. 3. Variation of Mass Fraction of CO with Temperature.

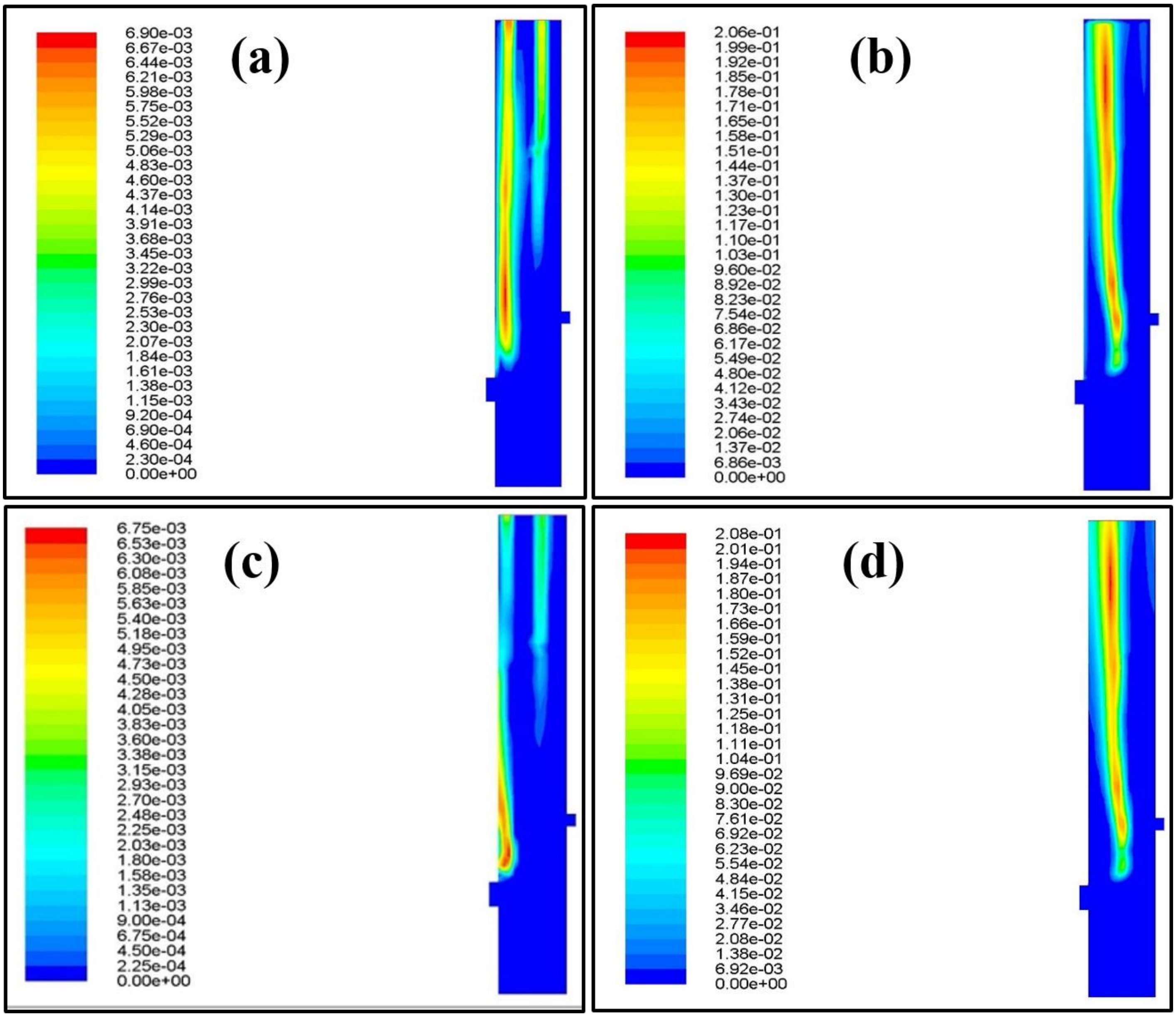

Fig. 4. Contour plot of mass fraction of H_2 (a and c) for Case-1, and (b and d) for Case-2 at 400K.

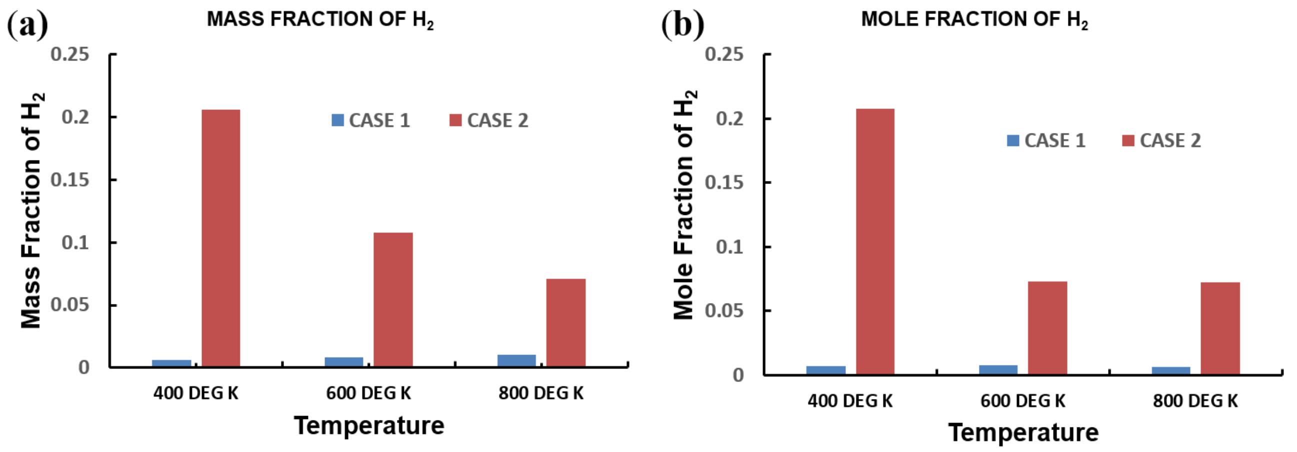

Fig. 5. Variation of Mass Fraction of H_2 with Temperature.

In contrast, in Case-2, where the sawdust particle size is 1 mm and the velocity is higher, the concentration of H_2 is greater, and the high-density region extends further from the inlet, which is likely due to the increased air velocity [4].

When the air preheating temperature is increased, the mass fraction of H_2 decreases. For both cases, at 600 K and 800 K, the higher temperature leads to a shift in the gasification process toward producing more CO_2 as more of the fuel undergoes complete combustion. This result suggests that, while higher temperatures enhance the overall gasification process, they limit H_2 production by promoting more oxidation of carbon-containing compounds into CO_2.

The mole fraction of H_2, as shown in Figure 5, also reflects these trends, with Case-2 consistently showing a higher H_2 yield compared to Case-1, particularly at lower temperatures. This is important because H_2 is a highly efficient fuel, and optimizing its production is crucial for efficient gasification. At higher temperatures, however, the increase in oxidation reduces the amount of available H_2, highlighting the need to balance temperature, particle size, and velocity for optimal syngas composition.

The results clearly demonstrate that both particle size and air velocity significantly affect the mass and mole fractions of CO and H_2 in syngas. Larger particle sizes and higher velocities lead to higher CO and H_2 concentrations at lower temperatures (400 K), while higher temperatures result in increased combustion, reducing CO and H_2 yields. These findings underscore the importance of controlling operating parameters to optimize gasification efficiency, as well as the syngas composition, based on the desired output.

4. CONCLUSION

A comprehensive 2-D Computational Fluid Dynamics (CFD) model for a Fluidized Bed Gasifier (FBG) using sawdust as biomass has been successfully developed and simulated in Ansys Workbench. The study focused on assessing the mass fraction and mole fraction of syngas generated through the gasification process while varying critical parameters, including air preheating temperature, inlet air velocity, and the particle size of the biomass fuel.

The analysis demonstrated that the syngas produced by gasification consists of a mixture of flammable and non-flammable gases. The results of the CFD simulation revealed that as the particle size of sawdust increased from 0.5 mm to 1 mm, the gasifier's performance significantly improved, reaching 85% efficiency at a preheating temperature of 400 K. Notably, at this temperature, the mole fraction and mass fraction of key fuel gases, such as CO and H_2, increased with the larger particle size. For instance, at 400 K, the mole fractions of CO and H_2 for 0.5 mm particles were 0.036 and 0.366, respectively, while for 1 mm particles, they were 0.271 and 0.249. This indicates a marked improvement in gas yield with larger particle sizes [14].

The simulations further indicated that as the air preheating temperature increased to 600 K, the mole fraction and mass fraction of CO and H_2 decreased. This is attributed to the increased combustion of fuel gases at higher temperatures, where CO is converted into CO_2, thereby reducing the overall fuel gas yield. The reduction in flammable gas fractions at elevated temperatures highlights the trade-off between operating temperature and fuel gas production efficiency. This study provides valuable insights into optimizing gasification parameters to enhance the performance of fluidized bed gasifiers. The results suggest that increasing particle size and optimizing air preheating temperatures can significantly improve syngas yield and overall gasifier efficiency. These findings offer a promising pathway for improving energy efficiency in biomass-based gasification systems, with potential applications in renewable energy and sustainable fuel production.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interests.

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