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IMPACT OF PARTICLE SIZE AND CARRIER GAS ON PULVERIZED BITUMINOUS COAL EMISSIONS: EXPERIMENTAL AND COMPUTATIONAL FLUID DYNAMICS ANALYSIS

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ABSTRACT

This study explores the influence of particle size and carrier gas on the clean and efficient combustion of pulverized 'Barapukuria' bituminous coal. Both experimental and numerical analyses were conducted to examine the temperature and fluid flow in a 1400 mm long vertical furnace with a 344 x *344 mm² interior cross-section. High-Temperature Air Combustion (HTAC) was employed to minimize NO_x emissions. The research focused on volatile matter and reactivity during combustion, evaluating their impact on NO_x, CO_2, and CO generation. CO_2 was used as a carrier gas to inject coal particles with sizes ranging from 0.001 to 0.02 mm. Results showed flue gas recirculation and varied devolatilization patterns with different particle sizes. Smaller particles produced less NO_x compared to larger particles, highlighting the potential for improved combustion and reduced emissions. Computational fluid dynamics (CFD) analysis also supported the experimental results. By optimizing combustion parameters, this study may contribute to achieve environmental sustainability.*

Keywords: *Pulverized bituminous coal, Particle size, Carrier gas, Combustion emissions, Computational fluid dynamics.*

1. INTRODUCTION

Energy is fundamental to our modern worldview, serving as the foundation for all human activities and civilization growth. Fossil fuels, such as coal, petroleum, and natural gases, are the most widely used energy sources, containing energy derived from ancient photosynthesis and produced naturally through the decomposition of buried organic matter (Liu *et al.*, 2017; Mei *et al.*, 2015). Coal, as the cheapest and most abundant fossil fuel, is a biofuel. During heating, its organic content undergoes pyrolysis, releasing carbon and volatiles (Dong *et al.*, 2019).

Coal remains the primary electricity generation source in many countries, providing 38% of global electricity in 2017, consistent with 30 years prior (Roberts, 2018). Used extensively in both developing and developed countries, coal combustion significantly impacts the environment, particularly the atmosphere. 'Clean Coal' technologies aim to reduce pollution emissions through coal treatment, modified combustion, or pollutant sequestration. Recent energy research emphasizes improving energy efficiency and reducing pollutant emissions to mitigate large-scale energy use and environmental disasters caused by the greenhouse effect. This study includes making coal particle size smaller, air staging, and air preheating to improve combustion efficiency. The combustion of coal and its volatiles can occur concurrently, sequentially, or with overlap, depending on specific combustion parameters. This combustion process involves a series of complex chemical reactions such as the following chemical equations (Saha *et al.*, 2017).

$$C_xH_yO_zN_lS_n + \left(\frac{x}{2} + \frac{y}{2} + \frac{z}{2} + n\right) O_2 = xCO + \left(\frac{y}{2}\right) H_2O + \left(\frac{1}{2}\right) N_2 + nSO_2 \quad (1)$$

$$N_2 + O \longrightarrow N + NO \quad (2)$$

$$N + O_2 \longrightarrow O + NO \quad (3)$$

$$N + OH \longrightarrow H + NO \quad (4)$$

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Coal combustion generates various gases, including NOx and SOx, as evident from the chemical reactions involved. Different parameters influence coal combustion, with various methods such as coal gasification, combustion of pulverized coal, and conventional combustion. This work focuses on pulverized coal combustion. Moderate Intensity Low-oxygen Dilution (MILD) combustion is an innovative technology in fossil fuel burning that offers ultra-low pollutant emissions, high thermal efficiency, enhanced combustion stability, thermal sector uniformity, and broad fuel flexibility (De Joannon *et al.*, 2007). Kiga *et al.* (2000) reported the first successful MILD combustion of highly volatile pulverized coal with a particle size of 74μm using a drop tube furnace. They emphasized its importance in increasing combustion efficiency while significantly reducing NOx emissions compared to conventional combustion. Suda *et al.* (2002) conducted an experimental investigation to explore the impact of air preheating on MILD combustion. After analyzing the characteristics of anthracite and bituminous coal, they found that increased combustion air temperature substantially reduced the ignition delay in coal particles. However, no previous study was found that studied the combustion efficiency and emission characteristics of 'Barapukuria' bituminous coal using experimental and CFD analysis. Therefore, this study focused on analyzing the available coal in Bangladesh to address this research gap.

Several articles on simulation-based numerical studies of fossil fuel combustion exist. Research indicates that NO is primarily formed from char-nitrogen in high-rank coal (anthracite), with the production/destruction process remaining unclear (He *et al.*, 2004). Mei *et al.* (2014) numerically investigated the effects of reactant injection velocity on coal MILD combustion, finding that increased primary air velocity significantly lowered the combustion temperature and reduced total NOx emissions. Tu *et al.* (2015) examined the MILD combustion characteristics of pulverized bituminous coal under O_2/N_2 and O_2/CO_2 atmospheres using simplified combustion models, suggesting that oxy-MILD combustion has a high potential for reducing NOx production. Ouyang *et al.* (2021) studied pulverized bituminous coal combustion without utilizing any carrier gas, which might lead to higher NOx emissions. These studies were significant as they highlighted the importance of reducing pollutant emissions from coal combustion without compromising efficiency. Our study also aims to emphasize the prospect of efficient and environmentally sustainable coal combustion and determine the specific parameters required to achieve this goal.

The International Flame Research Foundation (IFRF) conducted experimental studies in a 0.58 MW furnace, revealing substantial NOx reduction potential for MILD combustion of highly volatile bituminous coal (Weber *et al.*, 2015). However, the underlying pathways of NOx generation and destruction were not identified. Tamura *et al.* (2015) examined MILD combustion of bituminous coal in a bench-scale furnace, discovering that longer residence times for coal particles reduced total NOx emissions. Schaffel-Mancini (2009) employed CFD to assess the application of HTAC technology to pulverized coal boilers, finding that utilizing HTAC mode during startup reduced NOx emissions over longer periods of operation. A longer residence time was found essential for effective coal particle combustion in a recuperative furnace under MILD conditions (Saha *et al.*, 2014). Sung (2023) emphasized the importance of conducting further studies on coal combustion. Considering the time required to replace the existing global energy infrastructure with renewable energy sources, the world must achieve sustainability and energy efficiency simultaneously. In this context, our study aims to enrich the literature by providing a novel framework for determining optimized parameters for sustainable coal combustion.

Temperature plays a crucial role in accurately modelling coal combustion and gasification processes. High-Temperature Air Combustion (HTAC) technology, which involves the utilization of highly preheated combustion air, has garnered significant research attention over the past 15 years due to its energy-saving properties, enhancement of flame stability, and reduction of NOx emissions (Weinberg, 1996). Katsuki and Hasegawa (1998) examined the developmental history of HTAC technology and related research, while Weber *et al.* (2000) provided a comprehensive review of the progress made in 11 distinct HTAC processes. Given that our study involves a swirl burner, it is essential to understand its usage and implications.

The burner has been used in numerous commercial boilers in China, primarily as a flame stabilizer for low-volatile coals (Zhang *et al.*, 2007). To ensure adequate heating of the fuel-air mixture stream and improve ignition performance, primary air is separated into two streams, with the higher fuel particle-to-air mass ratio stream (C/A ratio) entering the preheating chamber. A newly designed furnace will be constructed for this combustion type, and the effects of certain parameters on exhaust characteristics will be observed. This research will focus on the influence of particle size and carrier gas, utilizing different carrier gases to transport pulverized coal to the furnace. High-grade bituminous coal from the Barapukuria Coal mine was used in the experiment.
Numerical simulations using various software have become feasible and attractive for enhancing coal combustion technology. Consequently, CFD simulation of pulverized coal combustion is a crucial aspect of this research. Flue gas recirculation is also employed to reduce pollutant emissions. However, no research has

examined the impact of particle size and carrier gas on exhaust characteristics and NOx reduction during pulverized bituminous coal combustion using flue gas recirculation, demonstrating the novelty of this study. In this context, the specific research objectives are, to investigate pulverized coal combustion characteristics, observe the effect of particle size on CO, CO_2, and temperature generation, and study the effect of particle size and carrier gas on NOx emission reduction.

The rest of the paper is structured as follows: Section 2 describes the detailed experimental setup and study methodology. Section 3 discusses the results obtained from this study. Finally, Section 4 concludes the paper, highlighting the novel contributions and implications of this study.

2. EXPERIMENTAL SETUP AND METHODOLOGY

2.1. Set-up Details

A unique experimental setup is needed to investigate the impact of particle size and carrier gas on pulverized bituminous coal exhaust characteristics. The experimental setup's precision is crucial for determining the nature of the outcomes. This section briefly describes the experimental details. Figure 1 presents a schematic representation of the pulverized coal combustion furnace. To reduce asymmetry caused by natural convection and ash deposition, the furnace is rectangular with a vertical axis. The furnace chamber is 1400 mm high, and the combustion chamber has a square cross-section of 344 mm² and a length of 585 mm. The furnace body is divided into three sections and is 10 mm thick. Fiberglass insulation, 75 mm thick, surrounds the furnace, allowing only about 10% of the total heat to escape through the walls. A swirl burner, which generates a steady, attached neutral flame with an equivalent ratio of 0.55 to stoichiometric ignition, is used. The oxidant is ambient temperature air, and natural gas serves as the burner's fuel.

Pulverized coal and carrier gas is introduced into the furnace through a well-insulated central jet with a 10 mm internal diameter. When the temperature exceeds the self-ignition temperature (1100K) of pulverized bituminous coal, coal particles are injected into the furnace using carbon dioxide (CO_2) as a carrier gas. Stable ignition and thermal equilibrium are achieved for all scenarios. Four different particle sizes are fed into the furnace at a constant flow rate of 1.48 kg/hr via the insulating central jet, using CO_2 as a carrier gas. The coal feed rate is controlled by the two-gate valve between the coal hopper and the piping system. In both circumstances, a massive recirculation vortex forms around the furnace center. An infrared thermometer was used to observe temperatures in the furnace midsection. Figure 1 is depicting a model of the furnace.

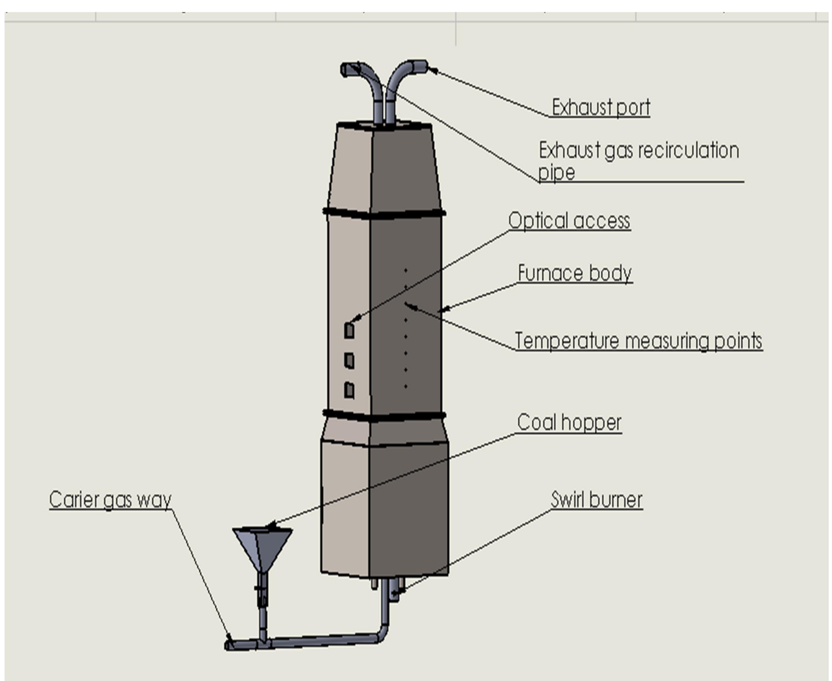


Figure 1: Design model of coal combustion furnace.

2.2. Set-up Components

Set-up components are described in this part of the article. Figure 2 is presenting some of the major components.

2.2.1. Furnace

The forced draft furnace used in this experiment combusts high-grade bituminous coal, utilizing atmospheric air for combustion and carbon dioxide (CO_2) as the carrier gas. The 1400 mm tall furnace is made of mild steel and consists of three parts: top, middle, and bottom. Pulverized coal combustion occurs in the middle section, which has an inner cross-section of 344 x 344 mm² and a height of 545 mm.

2.2.2. Coal Hopper

The coal hopper, located next to the furnace, serves as the primary source of pulverized coal. A special arrangement maintains a constant coal feeding rate. The mild steel coal hopper measures 80 mm long and 60 mm wide.

Figure 2: Different components of the setup (Left- Coal hopper, Middle- Furnace, Right- Burner).

2.2.3. Burner

The burner is a device that converts fuel into a controlled flame. The swirl burner, 38 mm in diameter and 60 mm long, creates swirling action to ensure proper air and fuel mixing. Air flows through a 3 mm clearance, while the natural gas supply line is 7.5 mm in diameter.

2.2.4. Piping System

The piping system transports coal to the burner, carries exhaust products, and recirculates flue gas. Insulated with material to prevent heat transmission, the mild steel (MS) pipe measures approximately 2600 mm long.

2.2.5. Air Compressor

The air compressor supplies combustion air at a specific velocity, forming a local diluted state inside the furnace with extensive internal recirculation, and reducing peak temperature by increasing air velocity.

2.3. Accessories

The accessories of this study includes Infrared thermometer, Flowmeter, Insulating material, Natural gas cylinder, and CO_2 gas cylinder.

2.4. Operating Conditions

Fast coal de-volatilization is required for combustion, involving oxidation within a diluted atmosphere. This includes substantial recirculation of flue gases to heat coal, combustion air, or both. High-momentum combustion air jets induce recirculation. Delivered velocity should not exceed 10 meters per second. Exhaust gas preheats combustion air, aiding coal de-volatilization. Two combustion scenarios differ in coal carrier gas: OX_{CO2} uses CO_2, while OX_{Air} uses air. When air is used, the combustion air flow rate is regulated to maintain the total air ratio. Four different particle sizes (0.001-0.005 mm, 0.005-0.01 mm, 0.01-0.015 mm, and 0.015-0.02 mm) are injected into the furnace at 1.48 kg/hr.

2.5. Methodology

Natural gas initiated the combustion process. A swirl burner ignited a natural gas and air mixture to heat the furnace to the self-ignition temperature of coal. Carbon dioxide gas, acting as a carrier, fed coal to the furnace after reaching the self-ignition temperature. The coal then combusted and sustained the combustion process. Nine ports in the middle part of the furnace allowed temperature measurement at different sections, with each port 63.5 mm apart. A DIGITECH QM7221 infrared thermometer measured the temperature. Coal was crushed into four particle size ranges: 0.001-0.005 mm, 0.005-0.01 mm, 0.01-0.015 mm, and 0.015-0.02 mm. All particle sizes were used at a constant feed rate of 1.48 kg/hr. A portion of the exhaust gas was recirculated to heat the coal (see Figure 3).

2.6. CFD Analysis

The 3D modeling of the furnace body was done by designing software "Solidworks-2016" and the analysis was done by simulating in the ANSYS FLUENT VR15.0 code (Sakolaree *et al.*, 2022). Different steps and parameters setting was very important to find out the proper result.

2.6.1. Solution Methods

We employed a finite volume method to discretize the governing equations for fluid flow and combustion. The pressure-velocity coupling was resolved using the SIMPLE algorithm, ensuring stability and accuracy in the solution. The discretization schemes used for convective and diffusive terms were second-order upwind and central differencing, respectively.

2.6.2. Mesh Sizes

The computational domain was discretized using a structured grid, providing a sufficient resolution to capture the flow and combustion characteristics. The grid was refined near the walls and regions of interest to enhance accuracy. The total number of cells in the grid was approximately 1 million, with an average cell size of 0.001 mm.

2.6.3. Mathematical Models

The combustion process was modeled using a two-step reaction mechanism, considering devolatilization and char combustion. We employed the Eddy Dissipation Concept (EDC) to model turbulent combustion, coupled with the Reynolds-averaged Navier-Stokes (RANS) equations. The standard k-ε turbulence model was utilized to capture turbulence effects.

2.6.4. Mesh Independence

To ensure mesh independency, a sensitivity analysis was conducted by refining the grid and comparing the results. After several iterations of mesh refinement, mesh independence was achieved when the cell size (y) was reduced to 0.0005 mm, and the total number of cells (x) in the grid reached approximately 2 million. We observed that further refinement did not significantly affect the key combustion parameters and species concentrations, indicating that our chosen mesh size provided accurate and reliable results.

2.6.5. Boundary Conditions

The boundary conditions were carefully specified to mimic the experimental setup. The inlet boundary condition involved injecting coal particles with sizes ranging from 0.001 to 0.02 mm, suspended in a CO_2 carrier gas. The coal particle size distribution was defined based on experimental measurements. The outlet boundary condition was set as an open boundary to allow the flue gas to exit the domain freely.

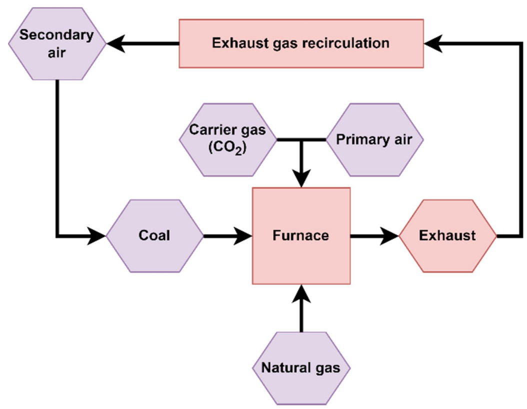


Figure 3: Flow diagram of experimental study.

3. RESULTS AND DISCUSSION

Two experimental and numerical studies were conducted using a medium-scale laboratory furnace to assess the impact of particle size on the combustion properties of pulverized high-quality bituminous coal with CO_2 as a carrier gas. The pulverized coal mass flow rate (1.48 kg/hr), secondary air temperature, and CO_2 content were kept constant. Four characteristics were observed for four particle sizes: temperature, carbon dioxide mass fraction, carbon monoxide mass fraction, and nitric oxide mass fraction in exhaust emissions.

3.1. Model Validation

To validate the model, the simulation output is compared with experimental data, focusing on temperature distribution. The model was numerically analyzed using bituminous coal properties and particle sizes of 0.001-0.005, 0.005-0.01, 0.01-0.15, and 0.015-0.02 mm. All particle sizes were used at a constant rate of 1.48 kg/hr. The maximum temperature differences between numerical and experimental values are 30.9 K for 0.001-0.005 mm and 26.7 K for 0.005-0.01 mm particle sizes. The dimensionless ratio (Y/Dj) indicates vertical positions, where Dj is the jet diameter and Y is the vertical distance from the jet exit plane.

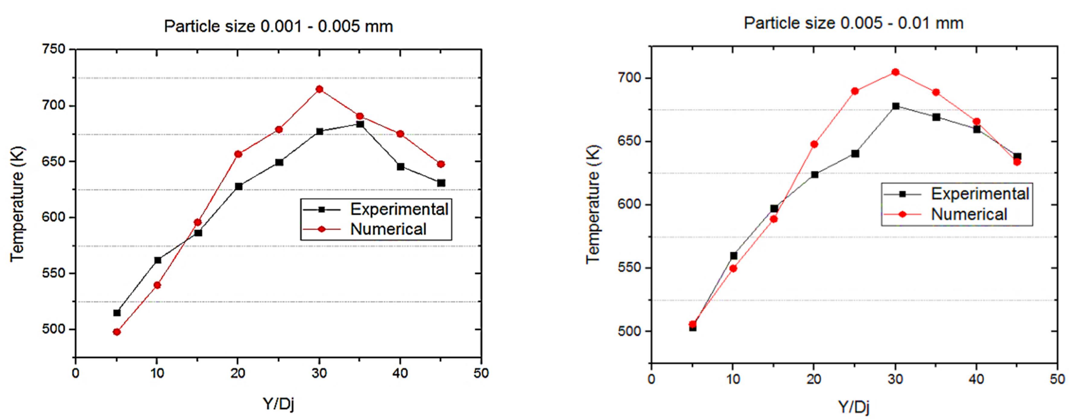


Figure 4: Experimental and numerical profile of temperature in the furnace.

Figure 4 shows that the numerical models used in this study generally replicate the experimental data well. However, they slightly under-predict CO and NO emissions, indicating that the simplified devolatilization model and combustion reactions are not yet sufficient to fully reproduce the experimental measurements. Discrepancies between simulation and experimental results in combustion studies can be attributed to the simplified models and assumptions, incomplete understanding of combustion mechanisms, uncertainty in input parameters, ignored influencing factors, limitations, and uncertainties in experimental measurements, as well as numerical accuracy and computational constraints (Saha *et al.*, 2017).

3.2. Temperature Contour

Figure 5 displays the observed furnace temperature profile, illustrating the temperature distribution within the furnace. Profiles for four particle sizes are shown, indicating a uniform temperature distribution. A comparison of temperature profiles for examples 1, 2, 3, and 4 revealed that smaller particle sizes result in higher furnace temperatures than larger particle sizes (see Table 1). This is related to the timing and location of volatile release and reaction for smaller particles. Devolatilization occurs earlier for smaller particles and completes by the end of the recirculation vortex, whereas it occurs later for larger particles. The only expected temperature difference is at the furnace's fuel jet outflow, where a significantly lower temperature is anticipated. The temperature profile deviates from the centerline and shows temperature variations at different points.

Table 1: Experimental temperature (Kelvin) data for different particle sizes in the middle part of the furnace.

Particles' size ranges from 0.001 to 0.005 mm	Particles' size ranges from 0.005 to 0.01 mm	Particles' size ranges from 0.01 to 0.015 mm	Particles' size ranges from 0.015 to 0.02 mm
515.7	503.6	500.1	594.3
562.3	560.3	557.4	552.3
586.9	597.5	601.2	598.7
628.4	624.1	619.5	615.1
649.6	640.8	636.9	640.5
677.5	678.3	674.6	652.4
684.1	669.7	654.3	659.5
646.3	660.1	627.8	627.8
631.6	638.9	597.9	588.8

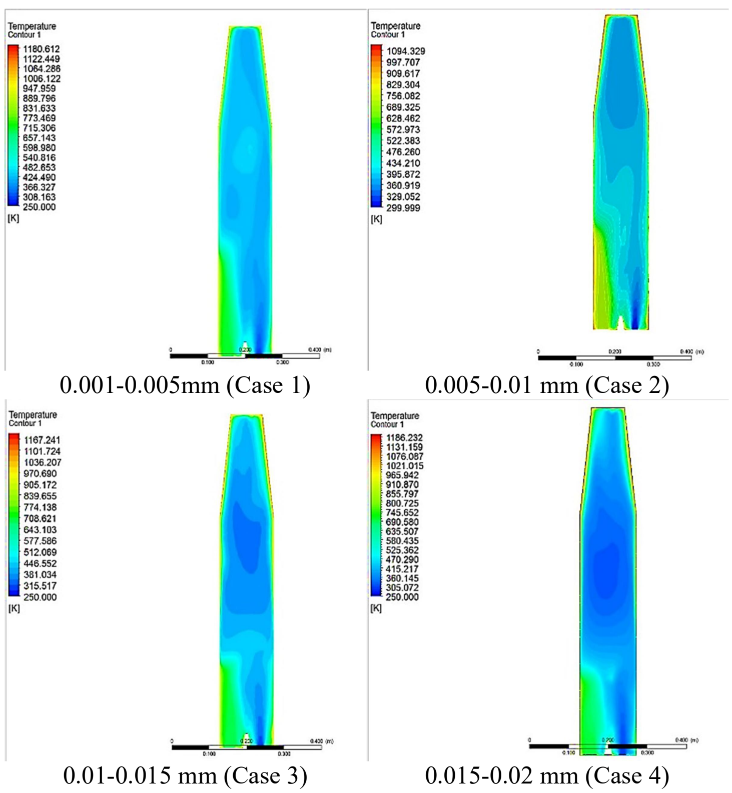


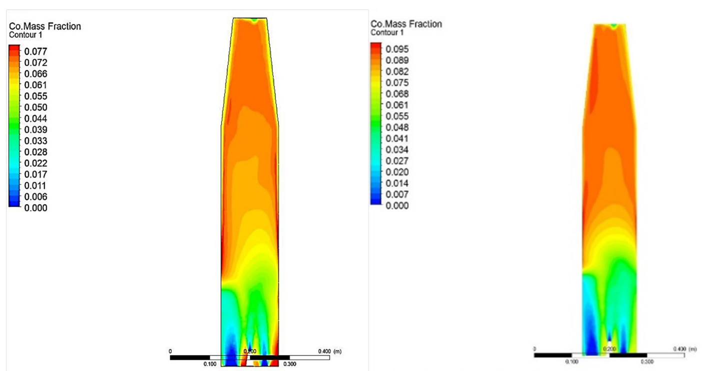
Figure 5: Temperature profiles.

3.3. CO Contours

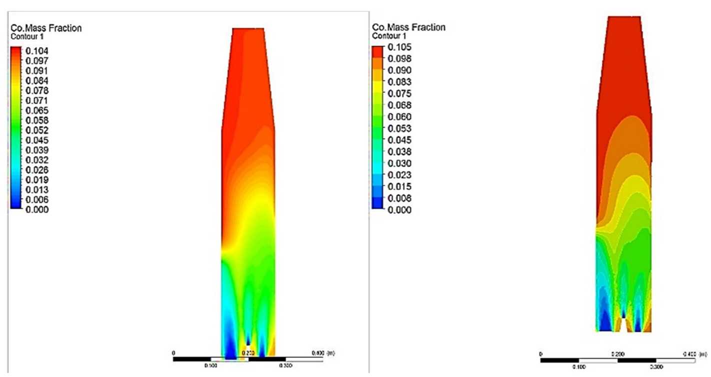
Figure 6 displays the observed CO concentration within the furnace. Smaller particle sizes generally exhibit lower in-furnace CO formation trends compared to larger particle sizes (see Table 2). The reduced CO production for small particles aligns with the results indicating a higher rate of volatile release and reactions for smaller particles at upstream locations, leading to more complete combustion and greater CO_2 production than larger particle sizes. Moreover, the CO concentration peak for smaller particle sizes is highest at the furnace center, while the peak for larger particles is found at the top of the furnace due to larger particles penetrating deeper into the furnace. This variation may result from several factors, including CO release as a volatile substance during coal devolatilization, CO production during the oxidation of volatile substances and char, and the influence of the water-gas reaction ($CO + H_2O \rightleftharpoons CO_2 + H_2$) on CO concentration. The CO concentration deviates from the centerline and exhibits different values at various positions.

Table 2: Observed numerical CO mass fraction data for different particle sizes in the middle part of the furnace.

Particles' size 0.001 to 0.005 mm	Particles' size 0.005 to 0.01 mm	Particles' size 0.01 to 0.015 mm	Particles' size 0.015 to 0.02 mm
0.044	0.041	0.048	0.045
0.049	0.048	0.052	0.060
0.056	0.055	0.060	0.068
0.061	0.068	0.071	0.074
0.066	0.075	0.078	0.080
0.072	0.082	0.86	0.083
0.070	0.089	0.93	0.091
0.069	0.085	0.99	0.098
0.067	0.089	0.104	0.105



0.001-0.005mm (Case 1) 0.005-0.01 mm (Case 2)



0.01-0.015 mm (Case 3) 0.015-0.02 mm (Case 4)

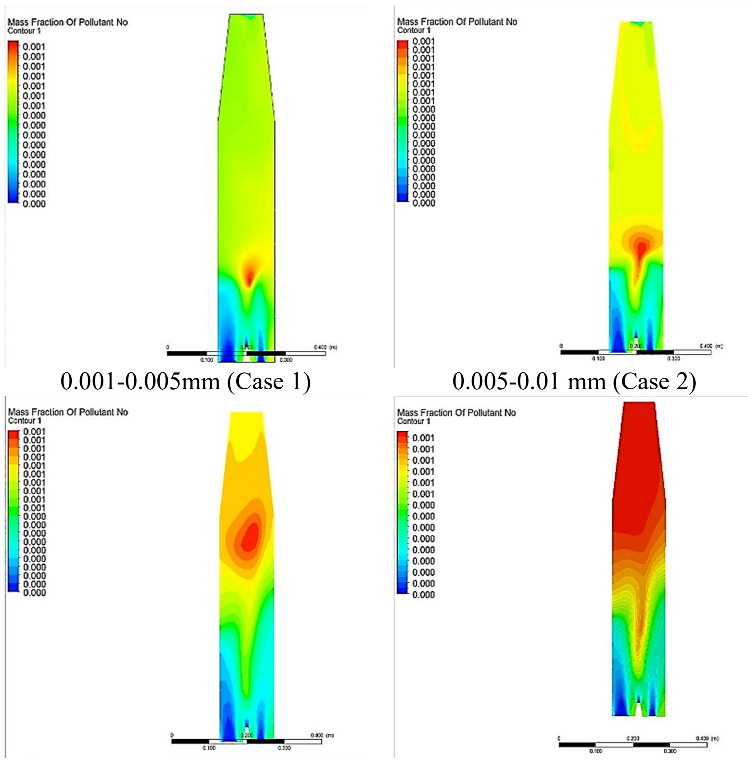
Figure 6: Concentration of CO.

3.4. NO Contours

Figure 7 presents the NO concentration profile within the furnace. NO emissions are measured for both smaller and larger particles, and the figure indicates that, under the same experimental conditions, larger particle NO concentrations are higher (see Table 3). However, due to NO re-burning processes, the overall NO emission rate from coal combustion is significantly larger than the measured local NO emission rate for both particle cases. The maxima for smaller particles occur near the jet exit, while the maxima for larger particles are observed towards the furnace's top. A notable increasing trend in NO concentration is observed as particle size increases.

Table 3: Observed numerical NO mass fraction data for different particle sizes in the middle part of the furnace.

Particles' size ranges from 0.001 to 0.005 mm	Particles' size ranges from 0.005 to 0.01 mm	Particles' size ranges from 0.01 to 0.015 mm	Particles' size ranges from 0.015 to 0.02 mm
0.001	0.001	0.000	0.001
0.001	0.001	0.000	0.001
0.001	0.001	0.001	0.001
0.000	0.001	0.001	0.001
0.000	0.001	0.001	0.001
0.000	0.000	0.001	0.001
0.000	0.000	0.001	0.001
0.000	0.000	0.001	0.001
0.000	0.000	0.001	0.001



0.001-0.005mm (Case 1)

0.005-0.01 mm (Case 2)

0.01-0.015 mm (Case 3)

0.015-0.02 mm (Case 4)

Figure 7: Concentration of NO.

3.5. CO_2 Contours

Figure 8 demonstrates that the CO_2 concentration within the furnace is higher for smaller particles than for larger particles. This is because more carbon is burned during the combustion of smaller particles compared to larger particles (see Table 4). The lower carbon consumption rate for larger particle sizes is associated with insufficient combustion residence time. Since larger particles are heavier than smaller particles, they take longer to burn significantly. The peak concentration occurs at the jet exit plane's closest point. A decreasing trend in CO_2 concentration is observed for all cases along the furnace's height. The findings indicate that coal particle devolatilization occurs at the jet exit plane, but volatile matter reactions begin at a specific furnace height, where volatile matters/gases effectively mix with incoming CO_2.

Table 4: Observed numerical CO_2 mass fraction data for different particle sizes in the middle part of the furnace.

Particles' size ranges from 0.001 to 0.005 mm	Particles' size ranges from 0.005 to 0.01 mm	Particles' size ranges from 0.01 to 0.015 mm	Particles' size ranges from 0.015 to 0.02 mm
0.608	0.597	0.590	0.584
0.598	0.591	0.555	0.552
0.579	0.580	0.537	0.524
0.570	0.568	0.503	0.513
0.566	0.557	0.485	0.479
0.541	0.544	0.461	0.461
0.538	0.529	0.446	0.442
0.519	0.511	0.432	0.409
0.505	0.497	0.414	0.386

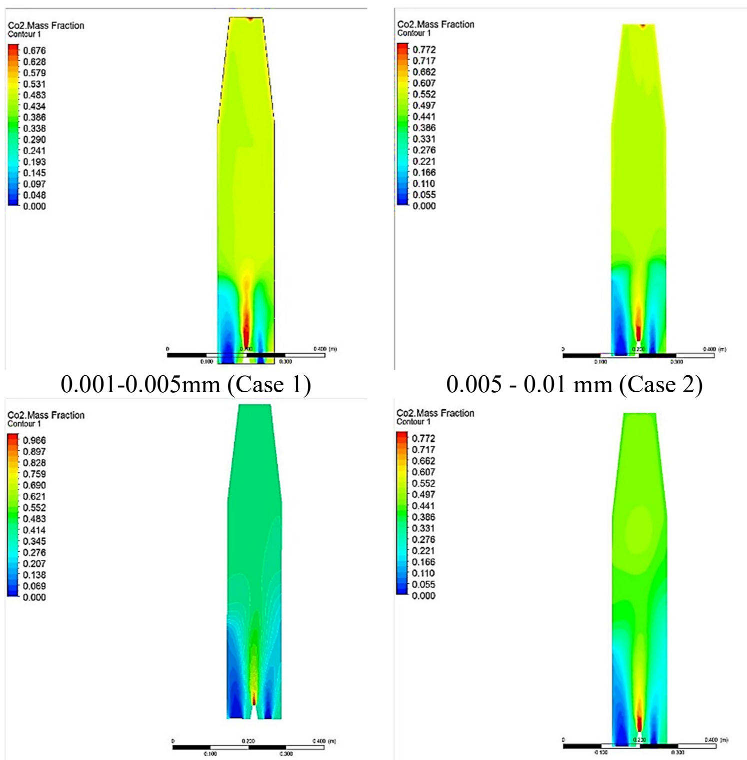


Figure 8: Concentration of $\mathbf{CO_2}$.

3.6. Carrier Gas

In this experiment, CO_2 is used as a carrier gas because of its easier availability and less expensive than other inert gases. It requires approximately 1500 degrees Celsius to turn CO_2 into C and O. So, the possibility of the formation of CO from C and O is much lower. As a result, CO_2 behaves as an inert gas, lowering overall pollutant emissions. Therefore, instead of utilizing air, it is employed as a carrier gas.

3.7. Validation of Results through Similarity and Contrast with Previous Studies

Previous studies have explored various methods of coal combustion for different types of coal, and their findings align with our study. For example, Sakolaree *et al.* (2022) observed a significant reduction in pollutant emissions during pulverized coal combustion as particle size decreased. Although their study parameters differed and only numerical simulation was used without an experimental setup or the use of carrier gas, our study provides robust support for their results. Similarly, Fan *et al.* (2020) demonstrated the use of fuel burning as a method in an air-staged combustor, but they did not employ a carrier gas as a preheater. These two concepts could be combined in future studies on coal combustion to further reduce NOx emissions. Future studies can focus on SOx reduction as well, which is a major contributor to acid rain (Zheng & Yan, 2023).

4. CONCLUDING REMARKS

This study investigates the effects of particle size and carrier gas on pulverized bituminous coal combustion characteristics, focusing on temperature rise and CO, CO_2, and NOx concentrations for four distinct particle sizes. The key findings are:

a. Smaller particles (0.001-0.005 mm) generate higher furnace temperatures, reaching up to 1148 K, while larger particles (0.015-0.02 mm) reach only 1040 K. The intense volatile combustion of smaller particles contributes to the higher temperatures.
b. CO concentration within the furnace is higher for smaller particles, indicating a substantially lower volatile release rate for larger particles.
c. NOx concentration is higher for smaller particles (0.001-0.005 mm) than for larger particles (0.015-0.02 mm). The global NOx emission rate from coal combustion is much higher than the experimental combustion method for all particle sizes due to NO re-burning processes.
d. Smaller particles (0.001-0.005 mm) have a higher maximum CO_2 concentration than larger particles (0.015-0.02 mm). To minimize NOx formation, particle size should be kept small, and furnace combustion temperature should not exceed 1700 K.

CO_2 is used as a carrier gas in this study, reducing overall exhaust emissions compared to using air. Argon and helium could yield better results but are more expensive. The findings can help develop strategies to minimize pollutant emissions. Future research could explore the impact of fuel injection angles and different burner types on combustion processes.

This study has important implications for environmental sustainability and fuel economy. By understanding the effects of particle size on combustion characteristics and pollutant emissions, this study can contribute to the development of strategies to reduce emissions of CO, CO_2, and NOx. These pollutants have significant environmental impacts, including climate change, air pollution, and acid rain. Minimizing these emissions helps protect the environment and supports efforts to combat climate change.

Besides this, the findings demonstrate that smaller coal particles yield higher furnace temperatures and more complete combustion, suggesting better fuel utilization and efficiency. Improved fuel efficiency can result in reduced fuel consumption and lower operating costs for power plants and industries relying on coal combustion.

By applying the insights gained from this study, it is possible to optimize combustion processes, reduce pollutant emissions, and improve fuel economy. These outcomes contribute to a more sustainable future and support the responsible use of coal as an energy source.

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