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Original scientific paper

COMPARATIVE NUMERICAL ANALYSIS OF COAL AND BIOMASS PARTICLE DISTRIBUTION IN AERO-MIXTURE CHANNELS

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ABSTRACT

To analyze the co-combustion process of coal and biomass in a steam boiler furnace originally designed for pulverized coal combustion, it is crucial to first investigate the dynamic behavior of particles within the aero-mixture channels. Due to differences in material properties and particle size distributions, the behavior of coal and biomass particles can vary significantly. This study numerically models particle dynamics using a simulation approach based on a previously validated Euler-Lagrange computational fluid dynamics (CFD) model. The simulation results reveal key differences in the trajectories and velocities of coal and biomass particles, primarily caused by variations in their density and size. The main objective of this research is to identify and quantify the factors influencing particle dynamics, as well as to determine the interdependencies between them. The findings aim to provide valuable insights for optimizing burner design and enhancing the efficiency of the co-combustion process. Furthermore, the results contribute to a broader understanding of biomass particle behavior in multiphase flows, which is particularly important in the context of transitioning towards sustainable and low-emission energy systems.

Keywords: Aero mixture; biomass; coal; co-combustion.

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1. INTRODUCTION

Environmental pollution (air, water, soil, etc.), resulting from the accelerated industrial development of modern society, has severe and far-reaching consequences for the health of humans as well as other living organisms. Thermal power plants that produce electricity by burning coal are among the major local polluters, and in many cases, they also exert regional environmental impacts. In numerous developing countries, coal remains the most commonly used resource for electricity generation, due to its stable reserves and economic viability. Coal-fired thermal power plants emit by-products of the combustion process (solid particles and flue gases) into the atmosphere. The possibilities for reducing pollutant emissions and increasing the efficiency of thermal power plants using conventional methods have reached their maximum, and in such a situation, even the slightest improvements in efficiency lead to a better position and higher competitiveness [1]. The goal of reducing greenhouse gas emissions has prompted the development of low-emission technologies such as combined cycles, carbon capture and storage, and co-firing of coal with alternative fuels. The increasing integration of intermittent renewable energy sources into power systems may cause grid stability issues and impose operational challenges on conventional power plants connected to the same system. Due to such fluctuations, a growing number of coal-fired power plants no longer operate solely at base load but are required to frequently adjust output, perform more frequent cold and warm starts, and operate at partial loads to reduce shutdown and restart costs. The energy efficiency, and thereby the environmentally friendly operation of a boiler, primarily depends on the aerodynamic characteristics of the furnace. One potential solution lies in the reconstruction and optimization of existing pulverized coal-fired plants. This strategy would involve running the plants on biomass, waste, or coal within a system that has been optimized specifically for those fuels. It is important to consider that different granulometric and chemical properties of these fuels significantly influence the aerodynamic behavior of the combustion process in the furnace. Numerous numerical and experimental studies support these findings, particularly those focusing on the distribution of fuel material with different particle sizes across milling lines. For example, in the study [2], a mathematical model was developed and validated to describe the flow of a gas-coal two-phase mixture in the aeromixture ducts of the OP650b boiler. In the study [3], numerical modeling was used to analyze the spatial distribution of coal and biomass in the separator, along with the impact of the separator on particle distribution. Study [4] investigates the influence of particle density on the operational characteristics of coal preparation systems. The authors of the study [5] use a numerical model to analyze the impact of mill load on the distribution of coal dust particles. Additional numerical and experimental research on the behavior of biomass particles in turbulent flows was conducted in studies [6,7] and [8]. Belošević et al. provide a comprehensive analysis of methods for predicting the co-combustion of coal and biomass in the study [9]. In the study [10], the aerodynamics of burner jets in tangentially-fired boilers are analyzed using CFD modeling and experiments to optimize combustion efficiency. Furthermore, CFD modeling is employed in [11] to investigate the distribution of pulverized coal within the mill-duct system of the As Pontes Power Plant, to improve coal flow and combustion efficiency. A 3D simulation of gas-solid flow in a coal powder separator was conducted by Babić [12], while Kozić et al. [13] analyzed flow behavior in the ventilation mill and aeromixture channel of the lignite-fired Kostolac B power plant, providing valuable insights for system optimization.

As shown in previous research, numerical modeling software plays a significant role as a leading tool for describing the phenomena and processes associated with these mechanisms. The OP650b boiler in Thermal Power Plant Tuzla faces similar, previously defined challenges. Therefore, before any experimental or numerical investigation of coal and biomass co-firing is carried out within the scope of this work, a numerical analysis of the aerodynamic behavior of the combined distribution of coal and biomass particles in the aero mixture channels was conducted. This research extends the numerical model from reference [2], which accurately captured the behavior of

coal dust particles in aeromixture channels. The current level of knowledge regarding the co-firing process leads to the conclusion that co-firing coal with biomass is considered an important step in reducing environmental emissions. While fuel variation alone is not the only solution for reducing harmful emissions, it is among the most cost-effective options. A review of previous studies mainly focused on coal distribution reveals the existence of certain issues during the process that negatively impact combustion efficiency. Inadequate and imprecise information regarding fuel distribution within the boiler furnace can result in abnormal combustion, steam and material overheating, as well as slagging and fouling. Therefore, before investigating flame aerodynamics, it is essential to first determine the proper distribution of the fuel mixture and identify the influencing parameters that affect the co-firing process.

2. NUMERICAL MODEL

The simulations in this study were performed using the commercial CFD software Siemens STAR CCM+, due to its advanced capabilities in modeling turbulent multiphase flows with two-way coupling between the gas and particle phases. The computational model is based on the Euler–Lagrange approach, where the continuous phase (air) is treated in an Eulerian framework and the dispersed phase (coal and biomass particles) in a Lagrangian framework, allowing for individual particle tracking.

The gas phase equations are solved using the Reynolds-Averaged Navier–Stokes (RANS) method, with turbulence modeled via the standard k–ε model. The interaction between the gas and particle phases is fully coupled, allowing momentum exchange. The particle motion is governed by Newton's second law, incorporating drag and gravity, while collisions with walls are modeled using restitution coefficients (0.9 tangential and 1.0 normal). Particle-particle interactions are neglected. The physical model assumes the following for the gas phase:

- the concept of the continuum is used to describe the flow;
- it is a single-component gas;
- the gas flow is steady;
- the gas flow is three-dimensional,
- the gas flow is incompressible;
- the gas flow is isothermal;
- the gas flow is chemically inert;
- the gas flow is turbulent.

For the particle phase, the assumptions include:

- two distinct materials (coal and biomass) with constant but different densities (1200 kg/m³ for coal and 600 kg/m³ for biomass);
- fixed particle shapes approximated as spheres;
- coal particles following a Rosin-Rammler size distribution (mean diameter D = 178 µm, spread parameter n = 2.23) based on validated data from previous research [2];
- biomass particles modeled with fixed cylindrical diameters of 3.6 mm, 1 mm, 0.7 mm, and 0.45 mm, chosen through an iterative simulation process and prior experimental data;
- no heat or mass transfer (particles retain constant temperature and mass);
- stochastic particle trajectories with partial kinetic energy loss upon wall collisions;
- the effect of the secondary phase on the primary phase is considered.
- particles lose a certain amount of kinetic energy upon impact with the internal walls;
- the particles move stochastically.

The computational domain was discretized using tetrahedral meshes, with mesh sizes ranging from 352,272 to 490,231 cells depending on the damper angle configuration. A visualization of the domain and boundary labels is shown in Figure 1.

Boundary conditions were defined as follows:

- Inlet: Uniform velocity of 23 m/s for the gas phase; particles are injected with the same velocity. Mass flow rates were 5.5 kg/s for coal and 1.488 kg/s for biomass.
- Outlet: Defined as pressure outlets with reference pressure set to 0 Pa. For particles, the "escape" condition was applied, terminating tracking at the domain exit.
- Walls: Reflective boundaries using restitution coefficients to account for energy loss upon particle collision.

An overview of all simulations and corresponding boundary conditions is presented in Table 1.

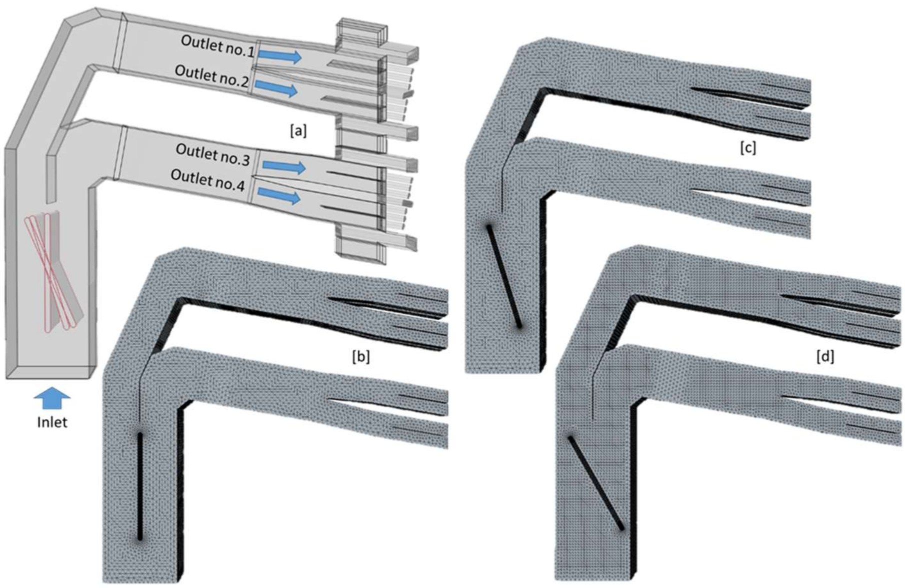

Figure 1. Air-fuel mixture channel with indicated inlet and outlet boundaries (a), and visualization of the discretized computational domain for different control damper angles (b, c, and d)

Table 1. Overview of Boundary Conditions for the Conducted Simulations

Type of Boundary Condition	Velocity of Aeromixture [m/s]	Inlet Particle Velocity [m/s]	Mass Flow Rade of Coal Particles [kg/s]	Mass Flow Rate of Biomass Particles [kg/s]	Coal Particle Size (Rossin-Rammler distribution) and Density [kh/m³]	Biomass Particle Size [mm] and Density [kg/m³]	Inlet Fluid Temperature [°C]	Control Damper Angle [°]	Tangential Restitution Coefficient	Normal Restitution Coefficient
Simulation No. 1										
Inlet Boundary	23	23	5.5	1.488	D=178µm n=2.23 σ=1200	**3.6** σ=600	190		/	
Wall Boundary					/			0	0.9	1
Simulation No. 2										
Inlet Boundary	23	23	5.5	1.488	D=178µm n=2.23 σ=1200	**1** σ=600	190		/	
Wall Boundary					/			0	0.9	1
Simulation No. 3										
Inlet Boundary	23	23	5.5	1.488	D=178µm n=2.23 σ=1200	**0.7** σ=600	190		/	
Wall Boundary					/			0	0.9	1
Simulation No. 4										
Inlet Boundary	23	23	5.5	1.488	D=178µm n=2.23 σ=1200	**0.45** σ=600	190		/	
Wall Boundary					/			**0**	0.9	1

Type of Boundary Condition	Velocity of Aeromixture [m/s]	Inlet Particle Velocity [m/s]	Mass Flow Rade of Coal Particles [kg/s]	Mass Flow Rate of Biomass Particles [kg/s]	Coal Particle Size (Rossin-Rammler distribution) and Density $[kh/m^3]$	Biomass Particle Size [mm] and Density $[kg/m^3]$	Inlet Fluid Temperature [°C]	Control Damper Angle [°]	Tangential Restitution Coefficient	Normal Restitution Coefficient
Simulation No. 5										
Inlet Boundary	23	23	5.5	1.488	D=178μm n=2.23 σ=1200	0.45 σ=600	190		/	
Wall Boundary					/			**17.24**	0.9	1
Simulation No. 6										
Inlet Boundary	23	23	5.5	1.488	D=178μm n=2.23 σ=1200	0.45 σ=600	190		/	
Wall Boundary					/			**29.8**	0.9	1

Since the validation process of the aero mixture channel process was carried out in the study [2] with a satisfactory degree of accuracy, the validation of the current problem will not be presented in this work. instead, the validated model from study [2] will be further developed by observing biomass particles in the aero mixture channel.

Simulating and analyzing the biomass distribution complements the lack of data related to the aerodynamic behavior of biomass particles within the aero mixture channel. This primarily involves comparing the dynamics of biomass and coal particles, their velocity values at the exits of the burners, as well as the distribution along the height of the burner itself.

3. RESULTS OF NUMERICAL SIMULATIONS

For the same position of the manual control damper, an initial analysis was conducted on the distribution of biomass particles of various fixed sizes and coal particles defined by the rossin-rammler (rr) distribution. Through an iterative investigation of biomass particle sizes ranging from 3.6 mm to 0.45 mm, it was determined that only biomass particles with a diameter of 0.45 mm exhibit aerodynamic characteristics comparable to those of coal particles.

This similarity is particularly significant in the context of fuel substitution in combustion systems originally designed for coal, as it suggests the potential for using fine biomass particles without the need for major modifications to existing infrastructure.

A visual inspection of the flow field (Figure 2) revealed a pronounced deviation in the aerodynamic behavior of larger biomass particles compared to coal particles, highlighting their reduced ability to follow the fluid streamlines and distribute uniformly within the flow channel.

This behavior underscores the critical role of particle size in achieving stable and efficient fuel transport, as only sufficiently small biomass particles can achieve the necessary flow conformity for reliable performance in coal-adapted systems. Consequently, ensuring proper particle size distribution during biomass preprocessing becomes essential to optimize flow dynamics and maintain combustion efficiency in retrofitted coal-fired systems.

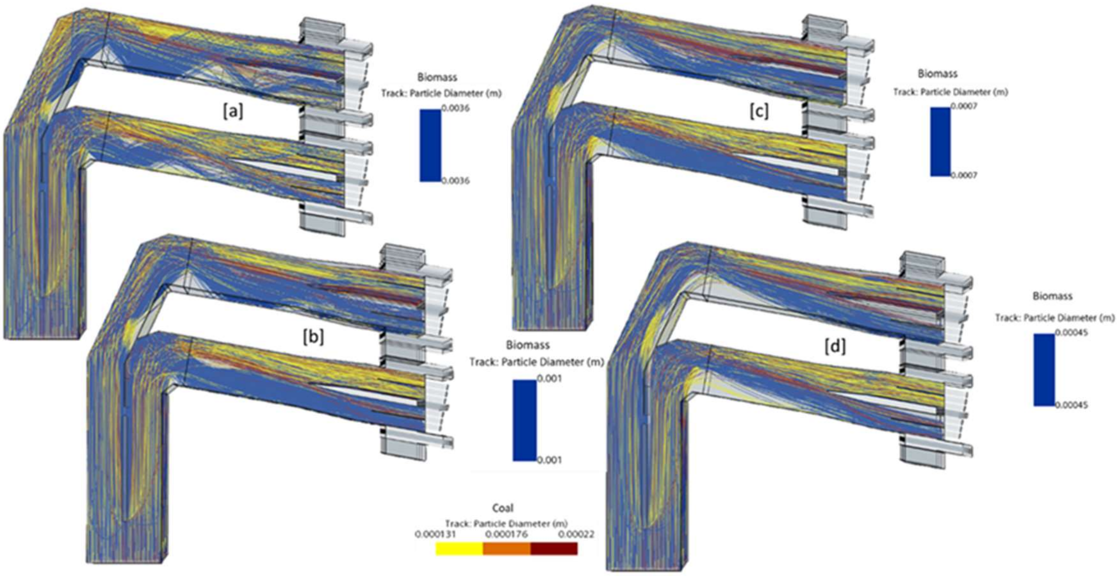

Figure 2. Comparative visualization of the trajectories of biomass particles with different fixed sizes about the trajectories of coal particles whose sizes are defined by the Rossin-Rammler distribution: a) biomass particle size is 3.6 mm, b) biomass particle size is 1 mm, c) biomass particle size is 0.7 mm, d) biomass particle size is 0.45 mm

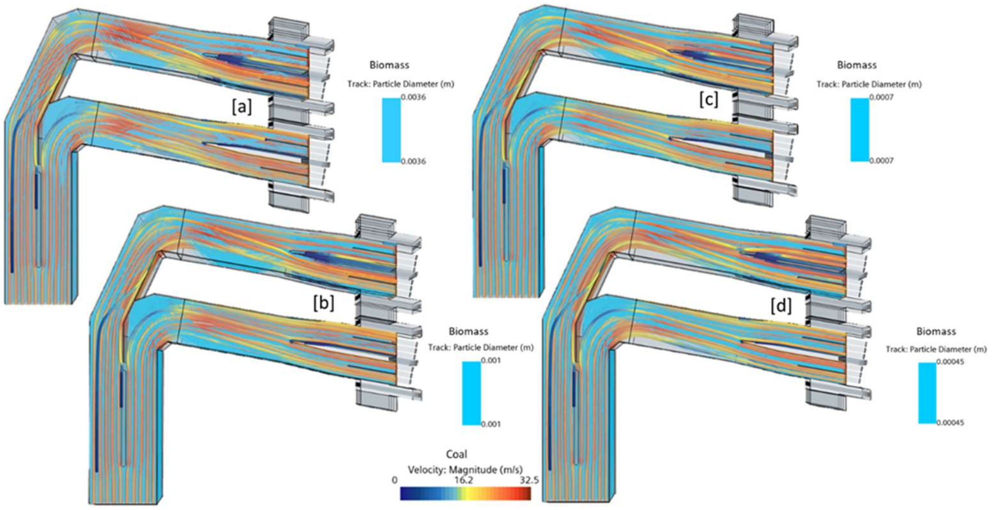

Figure 3. Comparative visualization of the trajectories of biomass particles with different fixed sizes about the gas-phase flow: a) biomass particle size is 3.6 mm, b) biomass particle size is 1 mm, c) biomass particle size is 0.7 mm, d) biomass particle size is 0.45.

Figure 3 presents a comparative illustration of the trajectories of biomass particles of varying sizes and their deviations from the primary gas flow path. The images underscore the importance of achieving dynamic equilibrium between the flow patterns of the primary and secondary phases within the aero mixture channel to ensure uniform biomass distribution along the burner height. This figure also illustrates the relationship between particle size and the resulting flow fields, clearly demonstrating that the inertia of biomass particles decreases proportionally with particle size reduction.

Although the flow simulations were performed using a fully three-dimensional computational domain, selected results are presented as two-dimensional fields for visualization purposes, a shown in Figures 4, 6, and 7. These 2D visualizations facilitate clearer presentation and allow for easier comparison of certain flow characteristics. However, they do not fully capture the spatial complexity of particle behavior, particularly phenomena such as secondary vortices, cross-flow dispersion, and interactions between particles and bounding surfaces. The three-dimensional geometry, along with the angle of particle impact, can significantly influence particle trajectories, causing dispersion not only in the direction of the primary flow but also transversely.

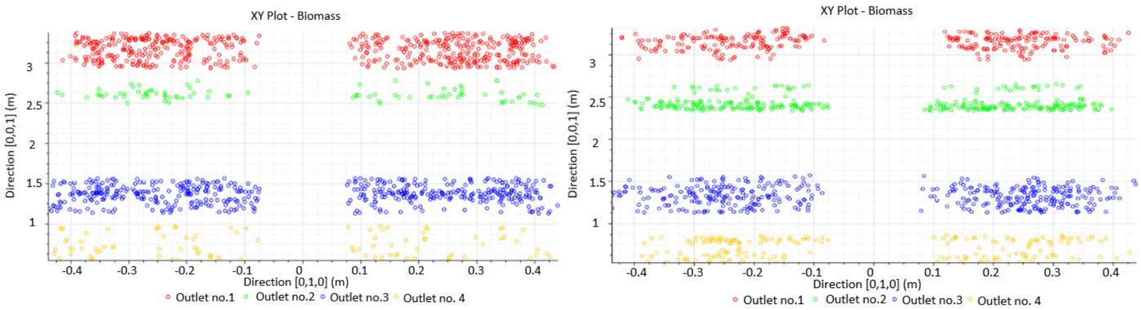

Figure 4. Visualization of biomass particle concentration along the burner height: (left) for particle size of 3.6 mm, (right) for particle size of 0.45 mm.

Consequently, two-dimensional simulations provide only a partial representation of these complex transport phenomena. While 2D representations are useful for identifying general trends and facilitating comparisons, the interpretation of results ultimately relies on the full three-dimensional simulations from which these sections are derived.

A detailed view of the outlet distribution of biomass particles along the burner height is provided in Figure 4, which displays two-particle distribution diagrams corresponding to different particle diameters. The left diagram in Figure 4, representing biomass particles with a diameter of 3.6 mm, clearly illustrates a disproportionately higher concentration of particles exiting through the upper sections of the burner. This uneven distribution suggests that larger particles, due to their higher inertia, tend to resist changes in direction and are less capable of following the intended flow paths within the burner structure.

In contrast, the right diagram in Figure 4, which depicts the distribution of 0.45 mm particles, shows a significantly more uniform distribution across all four burner levels. This uniformity is attributed to the lower mass and increased fluid responsiveness of the smaller particles, which allows them to be more evenly entrained by the carrier gas and distributed more symmetrically throughout the burner outlets.

Such differences in outlet distribution are not merely geometrical but directly influence combustion dynamics within the furnace chamber. Uneven particle loading can lead to localized temperature imbalances, incomplete combustion, and increased emissions, whereas a uniform distribution of fine particles promotes stable flame formation, consistent heat release, and improved overall efficiency of the combustion process.

Figure 5 presents a diagram showing the percentage load of each burner level for different biomass particle sizes, aimed at performing a statistical analysis of particle dispersion along the burner height. In the

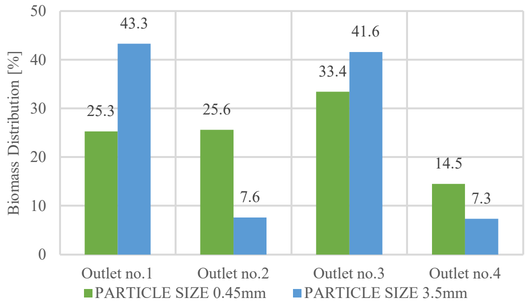

Figure 5. Diagram of biomass particle concentration along the burner height for different particle sizes.

case of biomass particles with a diameter of 3.5 mm, the diagram indicates a significant distribution imbalance, with a higher concentration observed at outlets No. 1 and No. 3. Conversely, a more uniform distribution is evident for cases involving finer particle granulation. If we examine the diagram illustrating the variation of particle velocity for biomass along the vertical axis of the burner (Figure 6), comparing both coarse and fine granulations, a clear distinction emerges in the range and behavior of particle velocities. Specifically, Figure 6 (left) presents the velocity profile for biomass particles with a diameter of 3.6 mm, where the recorded velocities reach up to approximately 21 m/s. This velocity range is notably lower than that observed for coal particles under comparable conditions, as illustrated in Figure 6-right. In Figure 6-right, it can be seen that coal particles attain considerably higher velocities, indicating a greater degree of acceleration and momentum transfer from the carrier fluid. This contrast highlights a fundamental aerodynamic discrepancy between coal and coarse biomass particles. The higher density and more favorable aerodynamic properties of coal enable it to be more effectively accelerated by the airflow, whereas larger biomass particles, with their lower density and higher drag coefficient, exhibit a reduced response to the flow field. As a result, the motion intensity, which reflects the dynamic behavior of particles within the flow, is significantly higher for coal particles. From an aerodynamic perspective, this discrepancy suggests a lag in response time and reduced entrainment efficiency for larger biomass particles. This lag not only affects particle transport and distribution but may also lead to undesirable combustion outcomes, such as delayed ignition, inconsistent flame propagation, or incomplete combustion. These findings underscore the importance of considering particle velocity profiles in the design and optimization of biomass injection systems, particularly when adapting existing coal combustion infrastructure. Ensuring that biomass particles can reach velocities comparable to those of coal is essential for maintaining stable combustion and minimizing performance losses in co-firing or biomass-only scenarios.

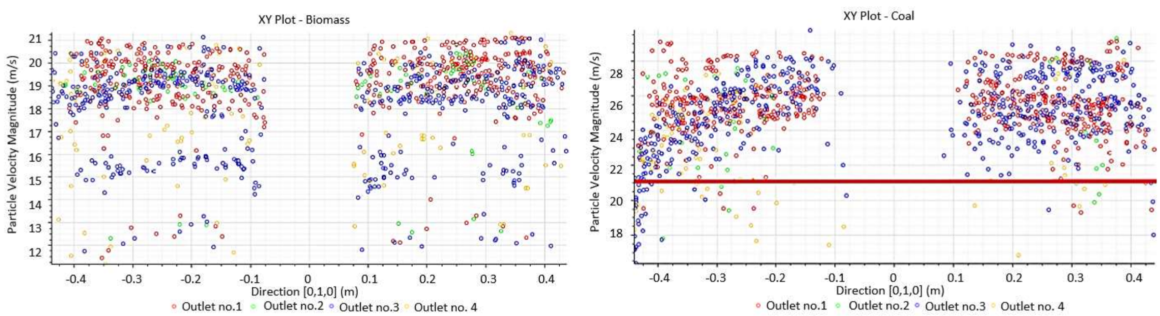

Figure 6. Visualization of biomass particle velocity variation (left) and coal particle velocity variation (right) along the burner height for a fixed biomass particle size of 3.6 mm.

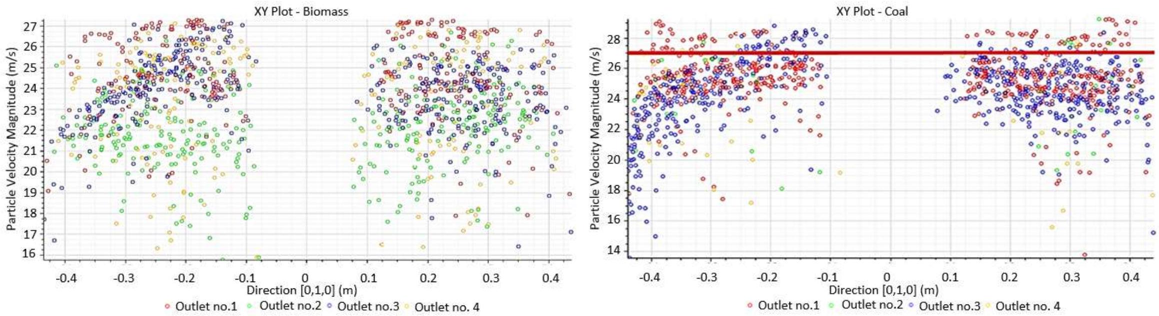

Figure 7. Visualization of biomass particle velocity variation (left) and coal particle velocity variation (right) along the burner height for a fixed biomass particle size of 0.45 mm.

Figure 7 (left) illustrates the velocity intensity distribution of biomass particles with a diameter of 0.45 mm at the burner outlet, while Figure 7-right provides a comparative visualization of the velocity distribution for coal particles under similar flow conditions. Upon analysis, these diagrams reveal a noticeable improvement in the velocity characteristics of biomass particles, with the 0.45 mm particles exhibiting a more balanced and consistent velocity profile in comparison to the more variable distribution observed in the case of coal particles. This relative improvement in flow dynamics suggests that with appropriate particle sizing, biomass can achieve a flow performance that closely aligns with that of coal, particularly in terms of momentum transfer and entrainment behavior within the burner geometry. However, while the 0.45 mm biomass particles demonstrate improved behavior, achieving a near-dynamic equivalence with coal particles particularly crucial for co-firing applications requires even finer granulation.

Based on the comprehensive flow and velocity analyses conducted, a particle diameter of approximately 0.45 mm has been identified as the critical size at which biomass particles begin to closely mimic the aerodynamic properties of pulverized coal.

At this size, the difference in behavior between coal and biomass becomes minimal, with an acceptable deviation of around 7% in aerodynamic performance parameters.

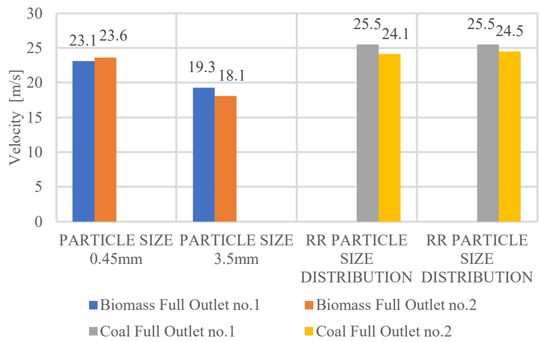

Figure 8. Diagram of biomass and coal particle velocity variation along the burner height

Further supporting this conclusion, Figure 8 presents a detailed diagram of velocity variation for both biomass and coal particles along the height of the burner. This figure provides a vertical profile of particle velocities, enabling a direct comparison of how different particle types accelerate and interact with the flow field at various burner levels. The diagram indicates that as the biomass particle size approaches the 0.45 mm threshold, the velocity profiles of biomass and coal begin to converge, indicating improved synchrony in particle transport. Such convergence is vital for ensuring even fuel distribution, consistent flame front development, and optimal combustion efficiency throughout the burner height. For analyzing the co-combustion process, it is also important to consider the distribution of biomass particles within the air-fuel mixture channel, depending on the angle of the manual control damper.

Figure 9 illustrates the distribution of biomass particles with granulation of 0.45

mm as a function of the damper angle. To analyze the co-combustion process of coal and biomass in a furnace of a steam boiler primarily designed for the combustion of pulverized coal, it is essential to first examine the dynamic behavior of different particles in the aero mixture channels. A clear understanding of how biomass and coal particles behave under varying flow conditions provides valuable insights into how to optimize fuel delivery and combustion efficiency. In this regard, the position of the manual control damper significantly influences the distribution pattern of particles along the burner height.

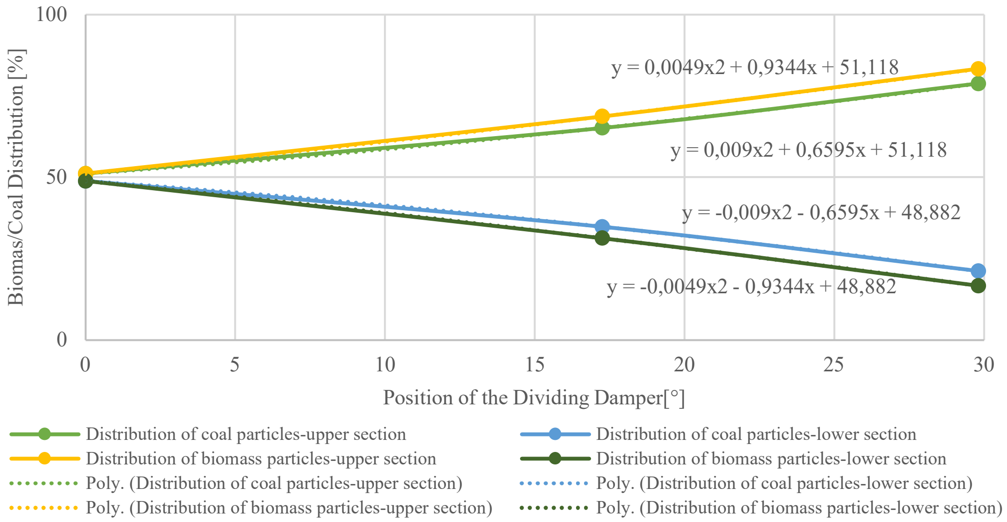

Figure 9. Functional representation of biomass and coal particle distribution for different control damper angles: 0°, 17.24°, 29.8°

By adjusting the damper angle, the velocity field and turbulence intensity within the air-fuel mixture channel change, which directly impacts particle trajectories, especially for biomass particles due to their lower density and greater sensitivity to aerodynamic forces.

The results presented in Figure 9 show a comparative overview of the particle load at the upper and lower burner outlets for both coal and biomass. The observed trends are fitted with linear polynomial functions, revealing a nearly linear correlation between the damper angle and particle distribution. Biomass particles exhibit more pronounced variation with changing damper angles, which is evident from the steeper slopes of the trend lines. For example, with increasing damper inclination, the concentration of biomass at the upper outlets increases, while it decreases at the lower outlets. This redistribution is a consequence of the altered flow field, which affects the inertia-driven behavior of lighter biomass particles. In contrast, the distribution of coal particles remains relatively stable, confirming their higher inertia and weaker response to variations in the flow pattern. This difference between the two fuel types is particularly important when designing co-firing strategies, as it highlights the need for fine-tuning damper settings to achieve a uniform and balanced fuel-air mixture. The established functional relationships shown in the diagram can serve as a basis for defining realistic boundary conditions in future computational simulations of the co-combustion process. In summary, the data demonstrates that the damper angle can be used as a control parameter to fine-tune the dispersion of biomass particles, ultimately improving the consistency and efficiency of combustion in existing coal-based boiler systems.

4. CONCLUSION

The analysis demonstrates that particle size plays a crucial role in the aerodynamic behavior of biomass within the flow field. Visual observations and computational results reveal that larger biomass particles significantly deviate from the fluid streamlines, unlike finer particles or coal, which are able to conform more closely to the flow dynamics. This discrepancy emphasizes the importance of ensuring a sufficiently small particle diameter approximately 0.45 mm during biomass preprocessing, as only at this size do biomass particles begin to exhibit aerodynamic properties comparable to pulverized coal. Proper particle size control is therefore essential for achieving stable and efficient fuel transport, uniform mixing, and effective combustion in retrofitted coal-fired systems. Larger particles, due to their slower response time and reduced entrainment efficiency, contribute to uneven loading, which may result in local temperature imbalances, delayed ignition, incomplete combustion, and increased pollutant emissions. Furthermore, the distribution of biomass particles within the air-fuel mixture channel is strongly influenced by the angle of the manual control damper. A clear understanding of how these particles behave under varying flow conditions allows for more effective fine-tuning of damper settings to ensure a balanced and homogeneous fuel-air mixture. These findings not only provide valuable insights for optimizing co-firing strategies but also establish functional relationships that can be used to define realistic boundary conditions in future computational simulations of the co-combustion process.

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Conflicts of Interest

The author declares no conflict of interest.

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