

Article

Utilization of Palm Frond Waste as Fuel for Co-Firing Coal and Biomass in a Tangentially Pulverized Coal Boiler Using Computational Fluid Dynamic Analysis

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Abstract: Renewable energy sources are becoming increasingly crucial in the global energy industry and are acknowledged as a significant substitute for fossil fuels. Oil palm fronds are a type of biomass fuel that can be utilized as a substitute for fossil fuels in the combustion process of boilers. Co-firing (HT-FRD) is a beneficial technology for reducing exhaust gas emissions generated by coal-burning power stations. By utilizing computational fluid dynamics (CFD), this study has modeled and evaluated co-firing palm frond residue (HT-FRD) with hydrothermal treatment into a 315 MWe boiler. In the simulation, six different HT-FRD co-firing ratios, 0%, 5%, 15%, 25%, 35%, and 50%, were used to demonstrate the differences in combustion characteristics and emissions in the combustion chamber. The data indicate that HT-FRD co-firing can enhance temperature distribution, velocity, and unburned particles. All in all, co-firing conditions with 5–15% HT-FRD ratios appear to have the most favorable combustion temperature, velocity, and exhaust gas characteristics.

Keywords: co-firing; hydrothermal treatment; palm frond (FRD); computational fluid dynamic (cfd); exhaust gasses

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1. Introduction

Researchers are studying renewable energy sources as a replacement for alternative fuels due to the global requirement for net zero emissions. Renewable energy sources are becoming increasingly crucial in the global energy industry and are acknowledged as a significant substitute for fossil fuels [1,2]. However, it is crucial to make significant efforts to mitigate global warming by reducing carbon dioxide (CO₂) emissions on a worldwide scale across all sectors [3]. Efforts are being made to mitigate CO₂ emissions from coal-fired power plants that exhibit high levels of CO₂ emissions. Several approaches have been assessed and suggested to accomplish this, such as including co-firing boilers [4]. Biomass can be utilized for power generation through two methods: dedicated combustion and co-firing. Co-firing offers benefits when used in current power plants, particularly those that rely on coal as their primary fuel source. These factors encompass improved combustion efficiency and reduced capital expenses [5]. Co-firing in boilers often involves the use of biomass fuel as a substitute fuel. Biomass co-firing is an economical approach to generating eco-friendly energy [1]. Biomass fuels exhibit a wide range of physical qualities, compositions, and structures with waste generation and fuel volume. However, compared to fossil fuels, biomass fuel has a larger proportion of volatile and ash content

[6]. The field of biomass co-firing has experienced significant advancements through the utilization of experiments and numerical analysis. A comprehensive description of combustion technologies, including the co-firing of coal and biomass, may be found in [7].

Oil palm fronds are a type of biomass fuel that can be utilized as a substitute for fossil fuels in the combustion process of boilers. Oil palm trees are globally recognized as one of the most prominent plant species. Approximately 70% of the waste generated in the production of crude palm oil consists of solid palm trash, including empty bunch leaves, stems, fronds, and shells. These waste materials are considered valuable sources of biomass energy due to their high calorific value. The calorific value of Indonesian oil palm fronds is 3941 kcal/kg [8]. Hence, oil palm fronds (FRD) can be suggested as a viable raw material for renewable energy sources in Indonesia. Oil palm fronds are a type of solid trash found on the plantation, particularly outside palm oil facilities. Laboratory tests have revealed that oil palm frond samples have a carbon (C) content of 44.37%, which is lower than the typical carbon content of coal. The hydrogen (H) content was found to be 5.51%, while the oxygen (O) content was 41.66% higher than the average oxygen content of coal. Additionally, oil palm fronds have very low nitrogen (N) and sulfur (S) content, specifically 0.46% and 0.10%, respectively [9].

Several innovative methods for enhancing the required properties of biomass fuel have been investigated, such as drying [10], hydrothermal treatment [11], pelletization [12], and carbonization [13]. One of these methods is hydrothermal (HT), which is employed as a preliminary treatment step before converting it into biomass feedstock. This involves applying water at a temperature ranging from 180 °C to 250 °C under high pressure (5–10 MPa) [14,15]. Multiple studies have demonstrated that hydrothermal processes result in higher energy density as a result of increased carbon content, calorific value, and hydrophobicity in biomass [16]. Furthermore, the hydrothermal method is deemed essential for processing palm oil biomass due to its exceptional conversion efficiency, capability of handling biomass in moist conditions, potential to generate diverse value-added products, and ability to eliminate several inorganic constituents, such as potassium content, from the biomass. However, it necessitates specialized equipment and intricate process control [17]. Nevertheless, the hydrothermal process presents various drawbacks that must be taken into account. These include substantial energy consumption, environmental repercussions stemming from energy utilization, and residue management outcomes, as well as the intricate nature of the process, which involves chemical reactions that necessitate the meticulous regulation of temperature, pressure, and time [18].

In addition, numerous researchers have examined the co-firing characteristics of oil palm frond biomass and coal [19] in conventional power plants without altering their design by utilizing computational fluid dynamics (CFD). Various types of palm oil waste materials, including empty fruit mark hydrothermal [20], palm kernel shells [21], and palm fronds [22], have been investigated. Computational fluid dynamics (CFD) is widely regarded as a very suitable method for evaluating the thermal characteristics of co-firing combustion [23]. Regrettably, there is currently no existing research that comprehensively examines and elucidates the specific attributes of palm oil frond combustion and coal co-burning through the utilization of numerical simulations on tangentially burned pulverized coal boilers. The primary aim of this study is to examine the combustion process of palm oil fronds (FRD) and coal as fuel in a 315 MW power plant. The specific focus is on analyzing the temperature distribution, gas velocity, and composition of CO, CO₂, and O₂ in the combustion chamber.

2. Hydrothermal-Based Co-Firing System

Under real conditions in coal-fired power plants, the process of mixing coal and biomass uses several tools, such as blending systems, pulverizers, conveyor belts, and bunkers or hoppers. In a coal-fired combustion chamber, there are several methods for co-firing biomass, such as injection, co-milling, pre-gasification, and parallel co-firing. In this

simulation, the injection method is used, in which samples of oil palm frond biomass from the fuel and engineering design laboratory (Serpong, South Tangerang, Indonesia) are dried and prepared to pass through a 60-mesh sieve [9] and then mixed with coal that has been filtered with a size of 200 mesh is fed into the combustion chamber through the primary air (PA) burner inlet simultaneously. This method is considered effective because of its lower and cheaper capital costs [24]. Therefore, injection co-firing was chosen to be analyzed in this study. It is assumed that FRD is injected with pulverized coal into the combustion chamber after being dried separately. Figure 1 shows the concept diagram of the FRD co-firing system, in which the raw FRD is dried at a temperature between 200 and 250 °C [25].

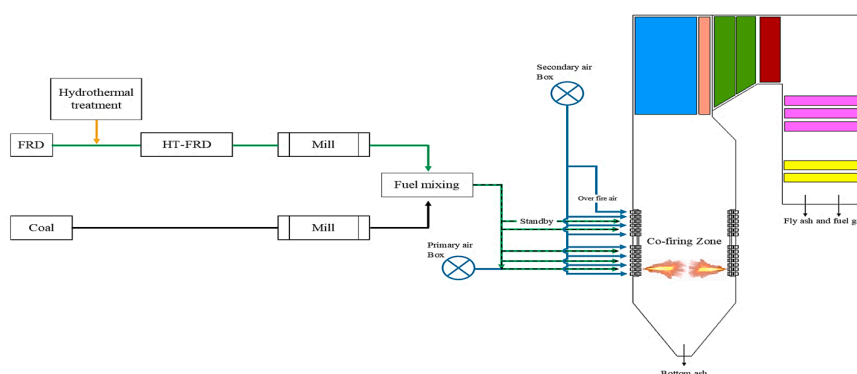


Figure 1. Conceptual diagram of the hydrothermal treatment palm frond co-firing system (HT-FRD).

This drying process aims to enhance the calorific value and properties of the FRD. Subsequently, the coal fuel is finely ground to the required particle size for efficient combustion within the boiler chamber. Following this, both fuel types are thoroughly mixed and injected into the combustion chamber and air, facilitated by respective heaters [20,26]. The superheater absorbs thermal energy from the combustion process, while the economizer generates steam specifically for the turbine. The flue gas, which is characterized by its comparatively low exergy level, is the fluidization gas in the bed to supply heat to the drying chamber. In this study, Figure 2 presents a schematic representation of the combustion chamber used, illustrating its dimensions and grid layout as well as the burner inlet located at the corner of the boiler. The boiler dimensions are 63.7 m high, 13.7 m wide, and 36.2 m long. This boiler is used in a pre-existing coal-fired power plant with a power generation capacity of 315 MWe adapted from Saputra I et al.'s 2023 reference [27].

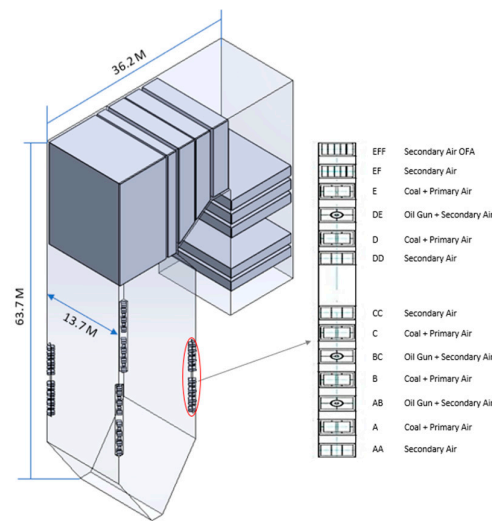


Figure 2. Design domain of a pulverized coal boiler simulation and inlet burner.

The configuration and area of the boiler's combustion system were established using the commercial software SOLIDWORK 2020. Afterward, the process was preceded by creating a simulation of the established system domain. In the case of co-firing simulation, the software ANSYS FLUENT 2023 R2 is utilized to calculate the velocity distribution, temperature distribution, and exhaust gas composition. The simulation includes the fundamental equations (enthalpy, mass, and momentum), heat transfer radiative, turbulence, and reactions in the gaseous phase and particles. This method is optimal for quantifying fluid flow, heat and mass transfer, chemical reactions, and interactions between solids and fluids. The research examines the co-firing FRD and coal performance using the CFD method [28]. CFD modeling proves to be significantly more efficient in terms of time and cost than physical experimentation while also being safe and easily scalable. Consequently, it is frequently utilized to validate experimental approaches. The CFD analysis aims to clarify combustion processes, including combustion temperatures and resulting exhaust gas concentrations. This study employed unaltered coal as the standard for combustion. The coal and FRD flow rates are determined based on the specified FRD mass fraction. This study investigates five distinct FRD mass fractions: 0% (representing 100% coal), 5%, 15%, 25%, 35%, and 50%. Observations are made on the temperature distribution and gas concentration generated during co-firing.

2.1. Governing Equations

The Eulerian–Lagrangian approach is frequently used to simulate co-firing as a two-phase reaction flow involving solid and gas phases. This technique uses the Navier–Stokes equations to examine the gas phase, regarding the solid phase as a different entity. Newton's equations of motion are employed to determine the trajectory of each particle, while a spherical technique is employed to simulate the interactions between particles [29]. The energy and mass transfer calculation for each particle is conducted to determine factors such as temperature and gas concentration. This technique allows for a more accurate simulation by tracking the motion of every individual particle within the system. The interactions between the gaseous phase and solid particles encompass mass, momentum, and energy, performed using the particle source method within a cell. The particle's state undergoes modification as it traverses its trajectory [30]. Mathematical calculations in this approach are primarily governed by heat transfer and fluid flow. Fluid dynamics is classified as a flow with high viscosity; each governing equation can be expressed in the following fashion:

$$\frac{D\rho}{Dt} + \rho \nabla \cdot \vec{U} = 0 \quad (1)$$

$$\rho \frac{D_u}{Dt} = -\frac{\partial p}{\partial x} + \frac{\partial \tau_{xx}}{\partial x} + \frac{\partial \tau_{yx}}{\partial y} + \frac{\partial \tau_{zx}}{\partial z} \quad (2)$$

$$\rho \frac{D_v}{Dt} = -\frac{\partial p}{\partial y} + \frac{\partial \tau_{xy}}{\partial x} + \frac{\partial \tau_{yy}}{\partial y} + \frac{\partial \tau_{zy}}{\partial z} \quad (3)$$

$$\rho \frac{D_w}{Dt} = -\frac{\partial p}{\partial z} + \frac{\partial \tau_{xz}}{\partial x} + \frac{\partial \tau_{yz}}{\partial y} + \frac{\partial \tau_{zz}}{\partial z} \quad (4)$$

$$\begin{aligned} \rho \frac{D}{Dt} \left(e + \frac{U^2}{2} \right) = & \rho q + \frac{\partial}{\partial x} \left(k \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left(k \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left(k \frac{\partial T}{\partial z} \right) - \frac{\partial (up)}{\partial x} - \frac{\partial (vp)}{\partial y} \\ & - \frac{\partial (wp)}{\partial z} + \frac{\partial (u\tau_{xx})}{\partial x} + \frac{\partial (u\tau_{yx})}{\partial y} + \frac{\partial (u\tau_{zx})}{\partial z} + \frac{\partial (v\tau_{xy})}{\partial x} + \frac{\partial (v\tau_{yy})}{\partial y} \\ & + \frac{\partial (v\tau_{zy})}{\partial z} + \frac{\partial (w\tau_{xz})}{\partial x} + \frac{\partial (w\tau_{yz})}{\partial y} + \frac{\partial (w\tau_{zz})}{\partial z} + \rho \vec{f} \cdot \vec{U} \end{aligned} \quad (5)$$

The fluid flow equations govern mathematical processes in quantitative physics calculations, specifically computational fluid dynamics (CFD). The equations incorporate density, mass conservation, specific mass fraction, temperature, enthalpy, turbulent dissipation rate, and turbulent kinetic energy as essential factor fluids. It is assumed that the representation of viscous flow is achieved through fluid dynamics principles [31].

2.2. Turbulence

The combustion chamber flow in this study exhibits turbulence due to fluid inertia, complex geometry, and high flow rates. Turbulence plays a crucial role in the co-firing model within the combustion chamber as it significantly influences heat and mass transfer. The k - ϵ turbulence model is commonly used in computational fluid dynamics (CFD) modeling to calculate turbulent combustion flow. This study utilizes the k - ϵ model to solve the Reynolds-averaged Navier–Stokes (RANS) equations for co-firing modeling. The k - ϵ turbulence model is highly regarded for its effectiveness and user-friendly nature [24], making it a popular choice in numerous industrial applications [32]. This model's two primary equations govern the turbulent dissipation rate (ϵ) and turbulent kinetic energy (k). It can be articulated as follows:

$$\frac{\partial}{\partial t} (\rho k) + \frac{\partial}{\partial x_i} (\rho k u_i) = \frac{\partial}{\partial x_j} \left[\left(u + \frac{u_t}{\sigma_k} \right) \frac{\partial k}{\partial x_j} \right] + P_k + P_b - \rho \epsilon - Y_M + S_k \quad (6)$$

$$\frac{\partial}{\partial t} (\rho \epsilon) + \frac{\partial}{\partial x_i} (\rho \epsilon u_i) = \frac{\partial}{\partial x_j} \left[\left(u + \frac{u_t}{\sigma_\epsilon} \right) \frac{\partial \epsilon}{\partial x_j} \right] + C_{1\epsilon} \frac{\epsilon}{k} (P_k + C_{3\epsilon} P_b) - \rho C_{2\epsilon} \frac{\epsilon^2}{k} + S_\epsilon \quad (7)$$

The variables P_b , Y_m , P_k , and μ_t denote long-term k production, turbulent viscosity, time effect, and the impact of variations in expansion on the overall energy dissipation rate, respectively. The equation determines the following values:

$$\mu_t = \rho C_\mu \frac{k^2}{\epsilon} \quad (8)$$

$$P_k = -\rho u'_i u'_j \frac{\partial u_i}{\partial x_j} \quad (9)$$

$$P_b = \beta g_i \frac{\mu_t}{Pr_t} \frac{\partial T}{\partial x_i} \quad (10)$$

$$\beta = -\frac{1}{\rho} \left(\frac{\partial \rho}{\partial T} \right) p \quad (11)$$

G_i , T , and Pr_t are the gravitational acceleration, temperature, and turbulent Prandtl numbers.

2.3. Radiation

Solid particle combustion, including heating, ignition, and charcoal burning, relies on heat transfer through radiation. Therefore, it is essential to comprehend the rate and amounts of volatile substances emitted during the devolatilization phase concerning temperature. The discrete ordinate (DO) radiation model is used in this simulation because it accurately considers the absorption of radiation heat during burning. The absorption coefficient is calculated using the weighted sum of gray gasses model (WSGGM) with a fixed value of 0.6 [33]. To address the issue of radiation heat transfer, this study utilized the P-1 approach, which relies on the expansion of radiation intensity [24]. The radiation model can be mathematically represented in the following manner:

$$\nabla \cdot (\Gamma \nabla G) = (a + a_p)G - 4\pi(a \frac{\sigma T^4}{\pi} + E_p) \quad (12)$$

$$\Gamma = 1/3 (a + a_p + \sigma_p) \quad (13)$$

$$G = 4 \sigma T^4 \quad (14)$$

$$a_p = \lim_{V \rightarrow 0} \sum_{n=1}^N \epsilon_{pn} \frac{A_{pn}}{V} \quad (15)$$

$$E_p = \lim_{V \rightarrow 0} \sum_{n=1}^N \epsilon_{pn} A_{pn} \frac{\sigma T_{pn}^4}{\pi V} \quad (16)$$

$$\sigma_p = \lim_{V \rightarrow 0} \sum_{n=1}^N (1 - f_{pn})(1 - \epsilon_{pn}) \frac{A_{pn}}{V} \quad (17)$$

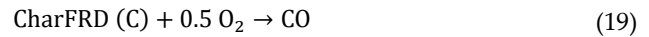
The variables A_p , σ , V , G , σ_p , and E_p represent the absorption coefficient, incident radiation, Stefan–Boltzmann constant, particulate presence, particle scattering factor, equivalent emission, and volumes, respectively, which all contribute to the equivalent absorption coefficient. Furthermore, f_{pn} , T_{pn} , ϵ_{pn} , and A_{pn} denote the emissivity, scattering factor, projected area, temperature, and particle n , respectively.

In general, the computation of mass, momentum, turbulence, and radiation in coal and biomass relies on a common equation. However, the specific parameters and models employed must be tailored to the unique features of each material. Coal exhibits a greater density in comparison to biomass. Biomass exhibits greater complexity in terms of its variability and reactivity, whereas coal is comparatively more stable yet emits a higher quantity of pollutants that necessitate regulation.

2.4. Reaction Mechanisms Particle Phases

The co-firing of coal and HT-FRD is recognized as a unique gas–solid flow system that induces chemical reactions. The model known as Eulerian–Lagrangian incorporates hydrodynamics into the analysis [34]. Coal particles and FRD chips are modeled separately as a two-phase discrete model. The Rosin–Ramler distribution approach is adopted for the particle distribution model [35]. Various reactions take place within the particle phase, notably during charcoal combustion. Charcoal undergoes oxidation, producing carbon monoxide (CO), which is then released into the combustion chamber as

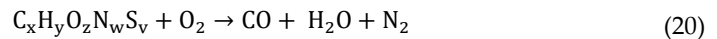
a large amount of gas. Acknowledging that charcoal produced from biomass generally exhibits greater reactivity and a higher heating rate than charcoal obtained from coal is crucial. This study utilizes a cohesive and all-encompassing response mechanism to assess the process of charcoal combustion in the presence of air. The process combustion of FRD and coal can be described as follows [20]:



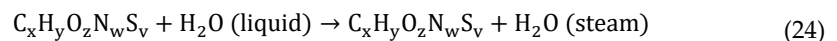
2.5. Reaction Mechanisms Gas Phase

The chemical composition and heat of formation of these components are determined through proximate and ultimate analyses. The co-combustion of palm fronds and coal involves two different combustion processes: the combustion of oil palm fronds and the combustion of coal. The coal combustion model consists of two independent stages: the devolatilization process and the gas combustion phase. The reference obtained [36,37], serves as a source for adjusting the kinetic rate parameters. The coal combustion equation is expressed in Equations (20)–(23). The combustion process of palm fronds goes through three stages, including drying, pyrolysis, and combustion, as evidenced by Equations (24)–(26). In addition, the benchmark of the kinetic rate of the combustion characteristics of palm fronds is obtained from references [29,38].

Coal combustion



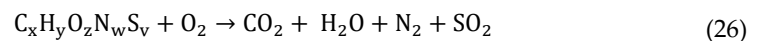
Frond drying



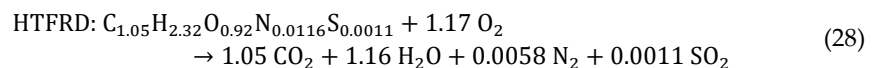
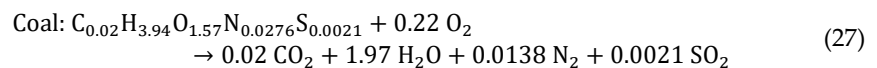
Frond pyrolysis



Frond combustion



The simulation equation model for coal combustion is shown in Equation (27), and the simulation equation for palm frond combustion is shown in Equation (28). As a reference, the kinetic rate of coal combustion characteristics and empty fruit bunches have been reported by [39].



The differences in combustion Equations (27) and (28) concerning the material composition in Table 1 can be caused by differences in oxygen content, calorific value, and volatile substances between coal and HT-FRD.

$$k = A e^{-\frac{E_i}{RT}} \quad (29)$$

All reactions in the gas or particle phases have their kinetic parameters listed in Table 2. The kinetic reaction rate coefficients are determined using Equation (29), which is derived from the Arrhenius equation, which incorporates the activation energy E_i [40]. It is presumed that the coal in question belongs to the lignite kind.

Table 1. Composition of coal and oil palm fronds utilized in this study [9].

Component	Coal	HT-FRD
Proximate analysis (as-received basis, wt %)		
Volatile matter	33.76	77.81
Fixed carbon	32.31	14.29
Ash	2.50	2.09
Moisture	31.43	5.81
Ultimate analysis (dry ash-free basis, wt %)		
Carbon (C)	46.96	44.37
Hydrogen (H)	3.29	5.51
Oxygen (O)	15.04	41.66
Nitrogen (N)	0.66	0.46
Sulfur (S)	0.12	0.10
Calorific value (as-received basis, Kcal/kg)		
HCV	4452	3941

Table 2. Kinetic parameters are utilized in particle and gas phases for their respective reactions.

Equation Reaction	A (s ⁻¹)	E _i (J. kmol ⁻¹ . K ⁻¹)
(18)	2.0 × 10 ¹¹	4.4 × 10 ⁷
(19)	6.8 × 10 ¹⁵	1.67 × 10 ⁸
(20)	3.0 × 10 ⁸	1.26 × 10 ⁸
(21)	1.9 × 10 ¹⁵	1.27 × 10 ⁸
(22)	2.75 × 10 ⁹	8.47 × 10 ⁷
(23)	1.3 × 10 ⁷	1.54 × 10 ⁸
(24)	1.2 × 10 ⁶	2.25 × 10 ⁶
(25)	1.5 × 10 ⁸	2.5 × 10 ⁷
(26)	1.0 × 10 ¹²	2.2 × 10 ⁸
(27)	3.13 × 10 ⁵	7.4 × 10 ⁴
(28)	1.1 × 10 ⁴	8.87 × 10 ⁴

3. Materials

In this work, the coal used in the existing power plant and the coal particles and FRD used in this experiment are detailed in Table 2, which presents their compositions. The coal was sourced from Kalimantan, Indonesia, specifically known as LRC, and has a very high water content. On the other hand, the FRD was sourced from a palm oil mill in Sumatra, Indonesia. The FRD used in this study was the as-received type of FRD, which had been dried. Based on the data in the table, Equations (27) and (28) can be formed for the chemical reaction equation model of coal combustion and HT-FRD. Chemical analysis usually provides a more comprehensive examination, while combustion equations generally rely on average or representative values obtained from the fuel.

4. Boundary Condition

The simulation involves categorizing boundary conditions into four types: wall, mass flow inlet, pressure outlet, and interior. Figure 3 shows the simulation domain of co-firing coal and palm fronds in a tangentially pulverized coal boiler. The primary and secondary airflow at the inlet are subjected to mass flow inlet conditions, whereas the boiler outlet is subjected to pressure outlet conditions. The primary air is the fuel feeder gas that moves through the pipes alongside coal particles, and FRD is introduced into the furnace via burner inlets A, B, C, D, and E. However, in this simulation, burner E (standby) is not operated, so burner E is designated as a wall. Additional air gas, required for combustion, enters the furnace through burner inlets AA, AB, BC, CC, DD, DE, EF, and EFF, flowing through the outer pipe.

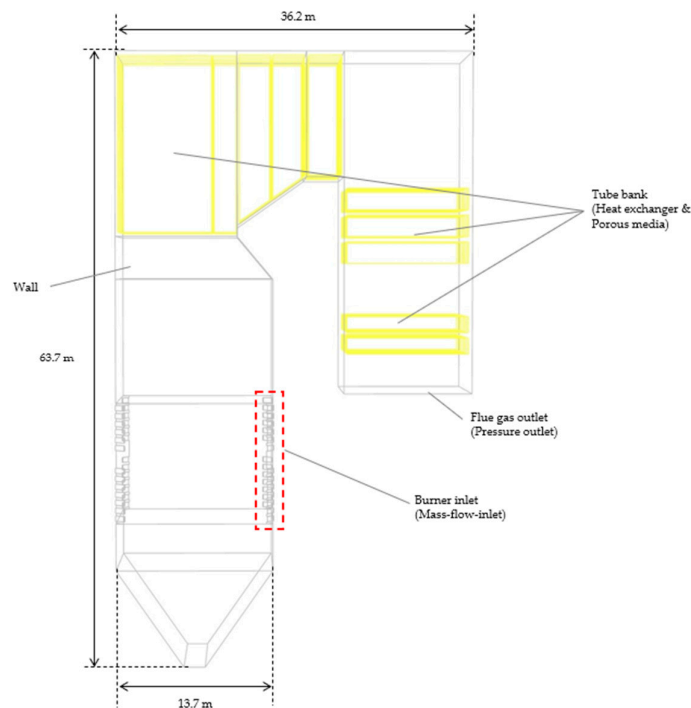


Figure 3. Domain simulation of a pulverized coal boiler.

Each particle is viewed as a solid sphere ranging from 60 to 200 mesh (74–250 μm), and the simulated power generator efficiently produces 315 MWe, achieving a fundamental combustion efficiency of 30%. Table 3 presents the boiler operating performance data. For the combustion simulation, the required amount of air is uniformly introduced into the chamber. The ratios of primary air, secondary air, and overfire air relative ratios remain unchanged compared to the scenario of pure coal combustion. Upon entering the combustion chamber, the particles undergo a series of ongoing events, which include heating, drying, devolatilization, the combustion of gasses and char, the creation of pollutants, and the emission of heat radiation [19]. The coupled algorithm, which is a method suitable for simulating complex geometries and multiple components, is employed to calculate the combined pressure and velocity of the Navier–Stokes equations. An analysis of the gas–solid two-phase flow is conducted using the Eulerian–Lagrangian technique. The Reynolds-averaged Navier–Stokes (RANS) equations are solved in the Eulerian domain to conduct the gas phase modeling.

The coal characteristics and HT-FRD setup information at each burner location are presented in Table 4. Throughout the simulation, fuel is injected in varying proportions based on the HT-FRD mix ratio of 5–50% across 16 burners (A–D burner areas, while the

E burner remains on standby). The domain is represented in a 3D combustion chamber model with a mesh count of 737,426 unstructured tetrahedral cells. The CFD simulation tracks the spatial distribution of temperature, velocity, and concentrations of exhaust gasses, including CO₂, CO, and O₂.

Table 3. Boiler parameter simulation.

Item	Boiler Operation		Simulated			
Case	1	2	3	4	5	6
Combustion type	Pure coal			Co-firing		
HT-FRD bleeding ratio (%)	0	5	15	25	35	50
Fuel mills (burn zone)		A B C D and E (standby)				
Coal feed rates (kg/s)	10.54	10.01	8.96	7.91	6.85	5.27
Biomass feed rates (kg/s)	-	0.53	1.58	2.64	3.69	5.27
PA ^a flow rate (kg/s)			97.62			
SA ^a flow rate (kg/s)			190.74			
OFA ^a flow rate (kg/s)			44.36			
Temperature of PA (K)			326.9			
Temperature of SA (K)			596.6			
Temperature of OFA (K)			596.6			

^a overfire air (OFA), secondary air (SA), and primary air (PA).

Table 4. Setup point of coal and HT-FRD properties on each burner.

Injection Name	Burner Zone	Temperature (K)	Total Flow Rate (kg/s)					
			1	2	3	4	5	6
Coal-Injection	A	329.8	11.14	10.59	9.47	8.36	7.24	5.57
	B	329.2	11.24	10.67	9.55	8.43	7.30	5.62
	C	330	10.90	10.36	9.27	8.18	7.09	5.45
	D	330.7	8.88	8.44	7.55	6.66	5.77	4.44
	E		Standby					
Frond-Injection	A	329.8	-	0.56	1.67	2.79	3.90	5.57
	B	329.2	-	0.56	1.69	2.80	3.93	5.62
	C	330	-	0.55	1.64	2.73	3.82	5.45
	D	330.7	-	0.44	1.33	2.22	3.11	4.44
	E		Standby					

5. Grid Independence and Validating the Computational Fluid Dynamic (CFD) Simulation

An independent study is required to establish the accuracy of the data findings. The objective is to align the grid domain with real-world conditions as closely as possible. Figure 4 displays the computational domain of the mesh for the pulverized coal boiler. Given the intricate nature of the PC boiler construction, it is imperative to streamline the model by segmenting it into multiple components. The simulation utilizes Ansys Fluent mesh software for the meshing process in pre-processing.

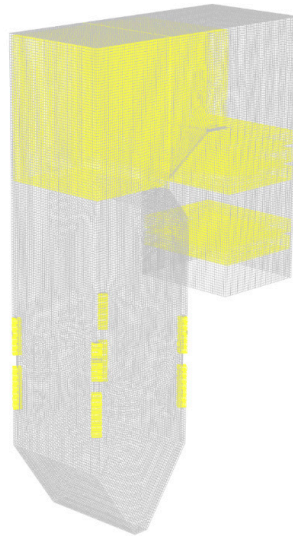


Figure 4. Mesh model of the pulverized coal boiler.

Three grid mesh models that were built previously were evaluated, as described in Table 5. The graphs in Figure 5 representing meshing #1 (coarse), meshing #2 (medium), and meshing #3 (fine) show a clear trend toward the actual boiler operating condition data at the design temperature of pulverized coal FEGT of 1258.2 K. This trend has been verified by various error deviations shown in Tables 5 and 6. Therefore, meshing system #2 is selected for simulation because of its optimal trade-off between numerical accuracy and computational cost.

Table 5. Mesh data for grid independence test.

Meshing Model	Elements	Nodes	Deviations Error %
Meshing #1	474.764	1956.757	10.04
Meshing #2	737.426	3007.994	3.8
Meshing #3	1386.233	5580.517	−4.86

Table 6. Mesh quality pulverized coal boiler on meshing #2.

Quality Aspect	Minimum	Maximum	Average
Element quality	2.7×10^{-3}	1	0.89
Aspect ratio	1	18	2.08
Skewness	1.4×10^{-10}	1	0.18
Orthogonal quality	7.8×10^{-8}	1	0.88

Figure 5 The accuracy of the meshing model must be checked by verifying the results of the grid independence test. Temperature data collection from simulation using a plane with a boiler height of 40 M at the average area temperature value obtained from the simulation for the entire meshing #1 data is 1384.5 K, for meshing #2 is 1306.1 K, and for meshing #3 is 1197.1 K.

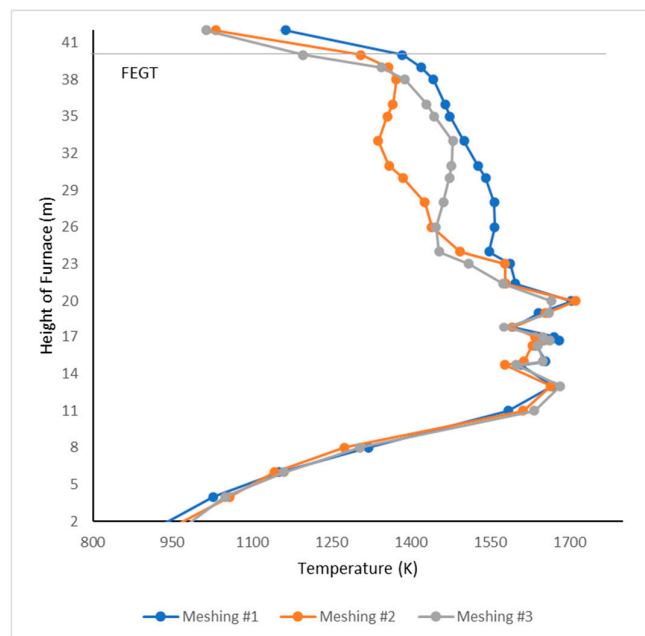


Figure 5. Grid independence.

To determine the accuracy of the simulation process, this study conducted a validation of the exhaust gas temperature between actual data and simulation data. In the actual operational data, there are seven points of the position of the exhaust gas temperature measuring instrument installed on the tube bank (heat exchanger) of the Pacitan PLTU boiler which are used for the validation test of operational data and simulation results shown in Figure 6 and further details can be seen in Table 7.

Table 7. Comparison of operating data and simulation results for validation.

Point	Unit	Reference (Operating Date) K	100% Coal Simulation (Model Validation) K	Validation Error %
1	Panel Division SH	1174.3	1222.1	−4.07
2	Platen SH	1056.8	1032.3	−2.32
3	Medium RH	974.3	916.3	5.96
4	Final RH	913	906.7	0.69
5	Final SH	876	830.9	−5.15
6	Low-Temperature SH	767.6	724.3	−5.64
7	Economizer	618.9	563.5	−8.95

Superheater (SH) and reheater (RH).

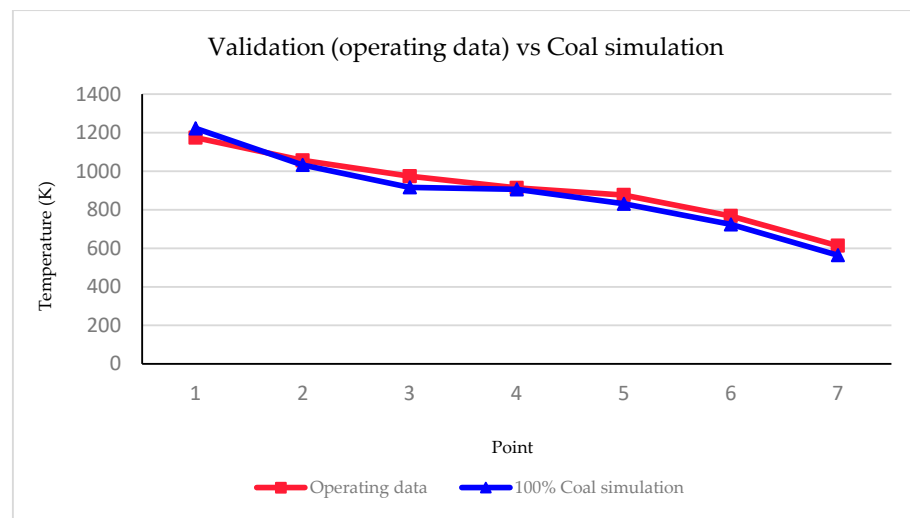


Figure 6. Validation of operating data and simulation result.

6. Results and Discussion

6.1. Effects of Co-Firing HT-FRD on Distribution Temperature

Simulation approaches were used to investigate the impact of HT-FRD co-firing on the combustion parameters of a pulverized coal boiler. Figure 7 depicts a 3D display model of the temperature distribution within the combustion chamber for each HT-FRD co-firing, with different mixing ratios. The simulation findings reveal a slight variation in gas temperature distribution, thereby increasing the proportion of HT-FRD combination, which generally results in a more vital flame and leads to a more consistent temperature as the height within the combustion chamber increases. Greater volatility leads to accelerated heat evaporation from combustion within the combustion chamber to the external environment of the furnace.

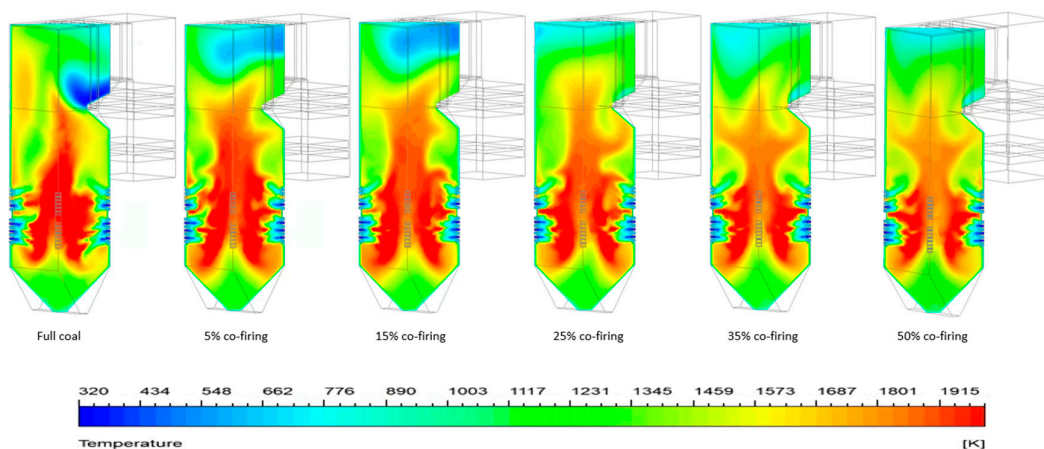


Figure 7. Temperature distribution under different blending ratios of HT-FRD across the furnace height.

This conclusion is supported by the temperature measurements in the FEGT region. Figure 8 illustrates the temperature distribution curve across the height of the furnace, ranging from the bottom ash to the furnace exit, for various ratios of HT-FRD co-firing.

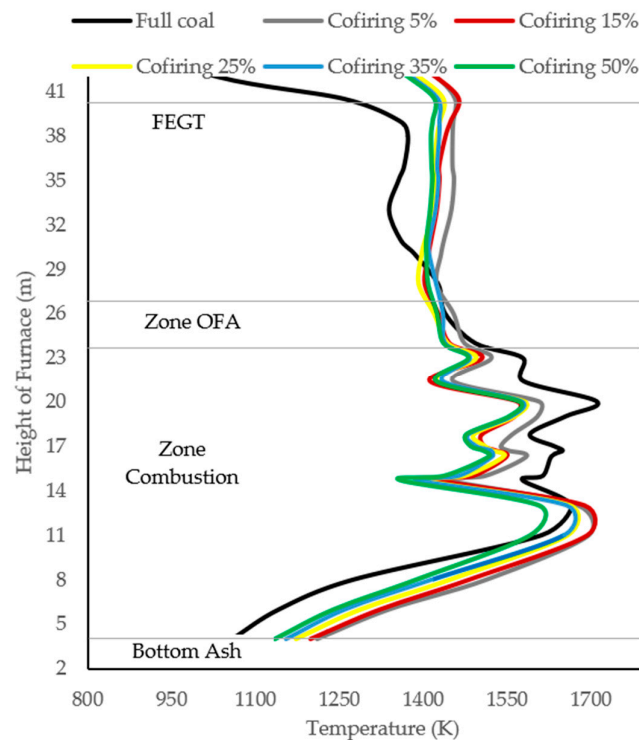


Figure 8. Simulation of gas temperature distribution under different blending ratios HT-FED across the furnace height.

The gas temperature distribution appears to be consistent across all co-firing ratios. There is a disparity in temperature between the combustion and OFA zones that goes all the way to the FEGT. As the biomass ratio increases, the maximum temperature falls from the primary combustion zone to the overfire air (OFA) zone.

However, in the FEGT section, the temperature rises with the HT-FRD co-firing ratio compared to pure coal. The highest combustion center temperature is found in the furnace section of the combustion chamber, with the 0% HT-FRD mass fraction at 1711 K, followed by 15% 1688 K (decrease of 1.3%), 5% 1662 K (decrease of 2.9%), 25% 1656 K (decrease of 3.2%), 35% 1653 K (decrease of 3.4%), and 50% 1607 K (decrease of 6%). When using a 15% mass fraction of HT-FRD in co-firing, a greater combustion temperature is found than a 5% mass fraction. However, the difference is not regarded to be significant. The mean temperature of the gas at the exit of the combustion chamber flue (FEGT) for HT-FRD mass fractions of 0%, 5%, 15%, 25%, 35%, and 50% are 1258 K, 1457 K (increase of 15.8%), 1464 K (increase of 16.4%), 1436 K (increase of 14.2%), 1427 K (increase of 13.4%), and 1420 K (increase of 12.9%), respectively. The temperature distribution profile indicates the most favorable coal combustion and HT-FRD co-firing performance when the HT-FRD mixing ratio is 15%. The combustion process involves four stages: ash formation, char combustion, devolatilization, and drying [41]. It is important to note that the combustion stages may vary for different fuels.

6.2. Effects of Co-Firing HT-FRD on Distribution Velocity

Figure 9 depicts the mean velocity distribution throughout the combustion chamber for varying HT-FRD co-firing ratios. The velocity increases as the HT-FRD mass ratio increases across the combustion chamber.

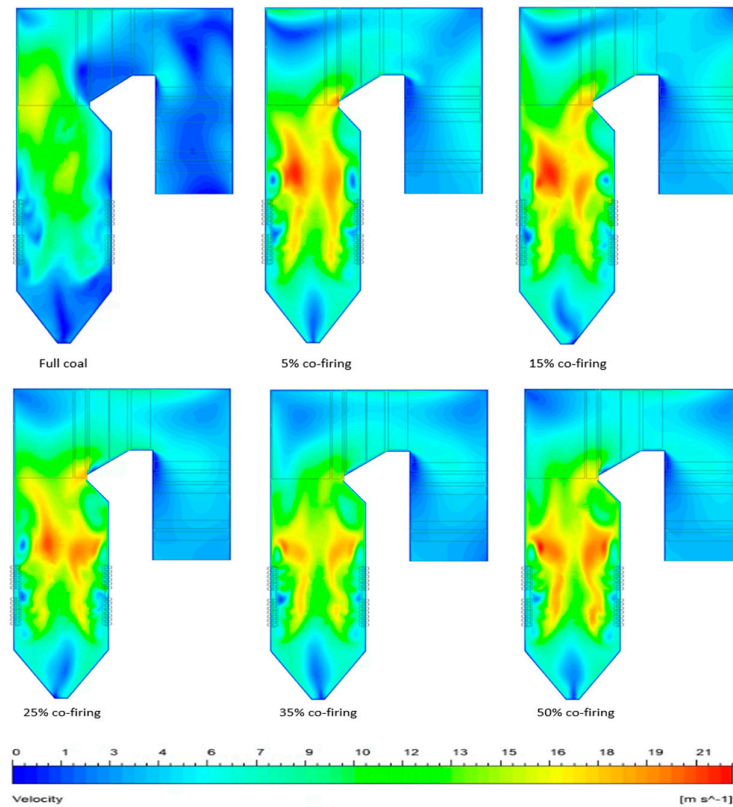


Figure 9. Velocity distribution across the combustor for each HT-FRD co-firing ratio.

The data presented in Table 2 show that HT-FRD particles have lower moisture content and higher volatile than coal particles. As a result, HT-FRD particles are swiftly dispersed throughout the combustion chamber, leading to devolatilization and an accelerated combustion process with an increased HT-FRD co-firing ratio. In the OFA zone, it can be seen that the velocity distribution increases up to 80%, for the 0% FRD mass ratio it is 7.77 m/s, followed by 5% at 13.77 m/s, 15% at 14.23 m/s, 25% at 14.06 m/s, 35% at 13.94 m/s, and 50% at 13.54 m/s.

Figure 10 demonstrates that the gas flow velocity in the combustion zone is rather consistent, regardless of whether full coal or palm frond co-firing is used as fuel. This indicates that blending the fuels does not significantly affect the distribution of velocity. The rapid speed in this area indicates the ongoing combustion reaction. In the FEGT zones, the gas flow velocities in all circumstances exhibit a minor decrease as a result of the combustion process being reduced up to the flue gas. In addition, the gas flow velocity concentration remains relatively constant across varied co-firing mass ratios, indicating that the flow properties in the furnace are not greatly affected.

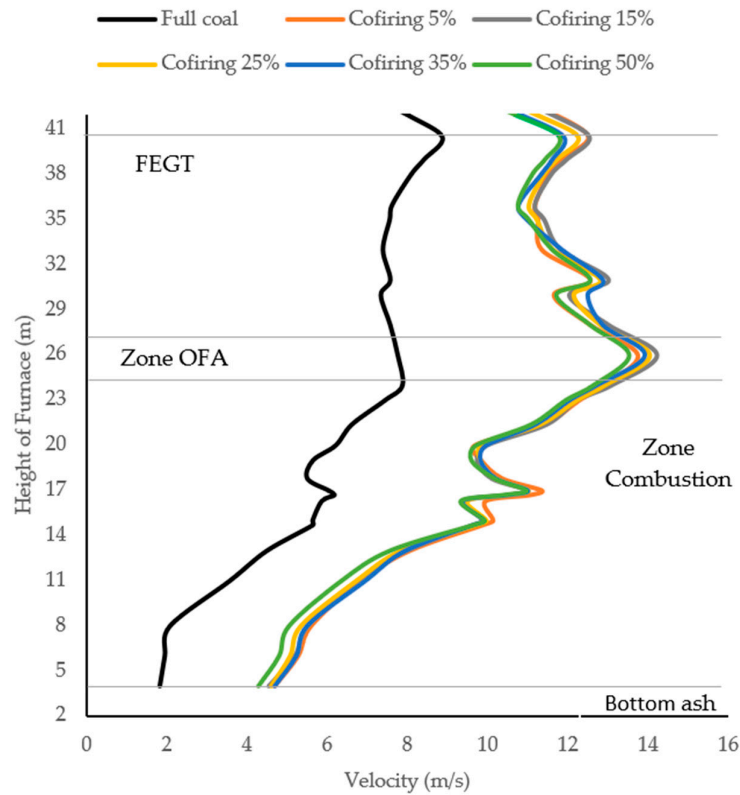


Figure 10. Mean velocity distribution across the combustor for all evaluated mass fraction.

6.3. Effects of Co-Firing HT-FRD on Gas Emission CO_2 , CO , and O_2

Figure 11 depicts the distribution profiles of CO_2 in the cross-section and the central location within the combustion chamber. The mean mass percentages of carbon dioxide CO_2 in the flue gas at the exit of the combustion chamber (FEGT) and the HT-FRD co-firing ratios resulted in a drop of up to 30.5%. Case 2 experienced a drop of 30.5% from 0.187 to 0.130. In case 3, there was a decrease of 25.1% from 0.187 to 0.140. Case 4 saw a decrease of 23.5% from 0.187 to 0.143. Case 5 had a decrease of 20.9% from 0.187 to 0.148. Finally, case 6 had a loss of 15% from 0.187 to 0.159. Therefore, a reduced ratio of thermal fuel replacement with biomass (HT-FRD) leads to a decreased concentration of carbon dioxide and CO_2 in the exhaust gasses. Thus, a low HT-FRD co-firing ratio results in a lower CO_2 concentration in the flue gas. The reactions illustrated in Equations (18)–(22) primarily convert carbon into CO_2 . Consequently, coal possesses a higher carbon content than FRD. The inclusion of HT-FRD diminishes the carbon content while enhancing the volumetric heat capacity and the propensity of the flame to spin.

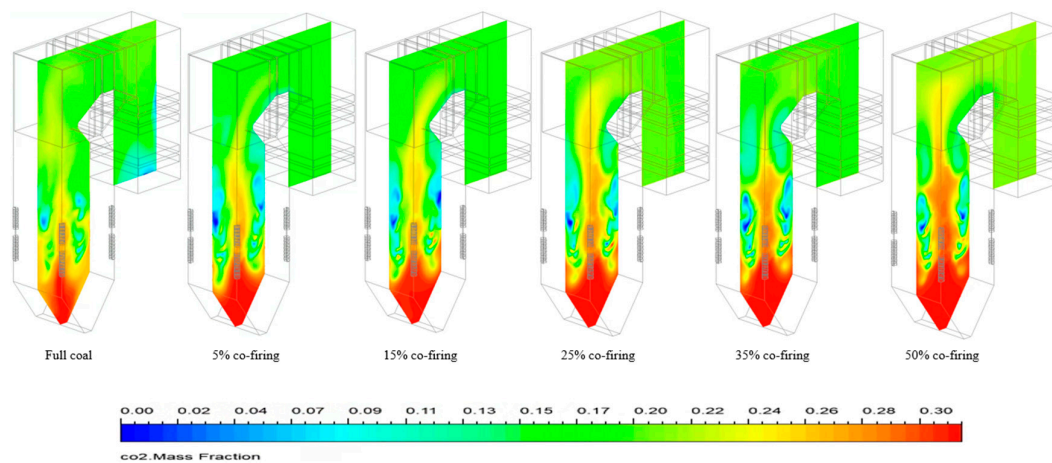


Figure 11. CO₂ distribution cross-sectional profile across the HT-FRD co-firing combustor ratios.

Figure 12 demonstrates that including biomass HT-FRD into the fuel in the combustion zone can gradually decrease flue gas emissions, particularly CO₂, by reducing combustion reactions. The research demonstrates that the co-firing of palm frond biomass with coal can result in a reduction of CO₂ emissions when compared to the complete combustion of coal. This suggests potential environmental advantages.

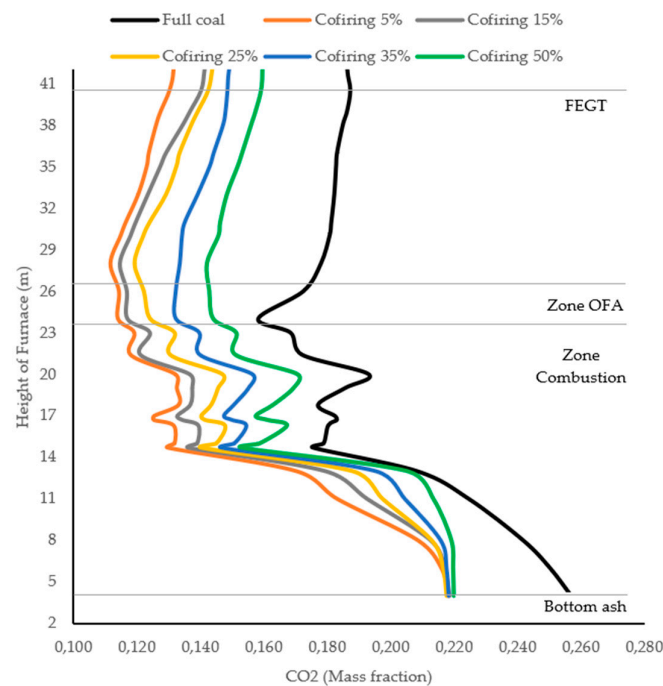


Figure 12. CO₂ distribution at the center across the height of HT-FRD co-firing combustor ratios.

Figure 13 provides valuable insights into CO gas concentration traversing the combustion chamber during co-firing. Unlike total coal combustion, HT-FRD co-firing has properties that can increase the concentration of CO during combustion. An increase in the proportion of HT-FRD results in a higher level of CO concentration produced during the combustion process.

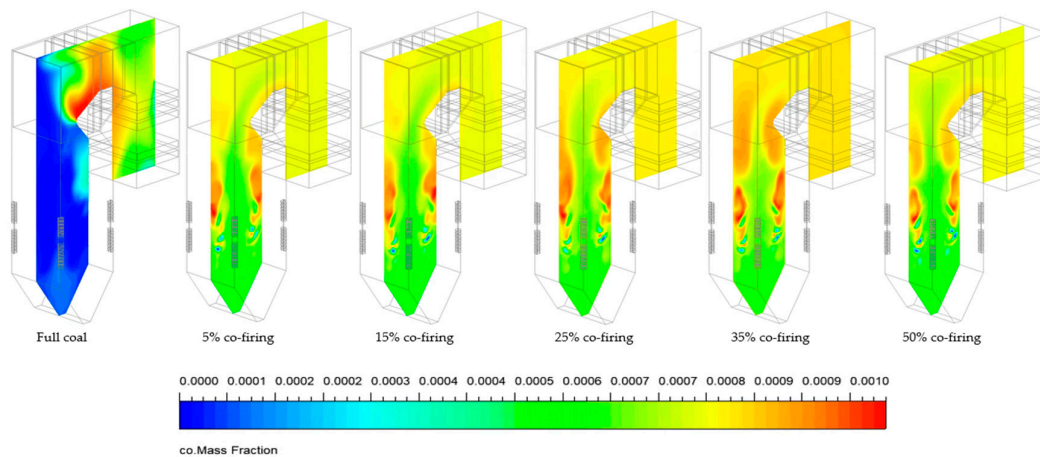


Figure 13. CO distribution cross-sectional across the HT-FRD co-firing combustor ratios.

Nevertheless, augmenting the co-firing ratio of HT-FRD does not significantly alter the final result. The differing volatile matter levels between coal and HT-FRD can be considered the cause of this outcome (as shown in Table 2) because they are readily oxidized at high combustion temperatures, facilitating the formation of CO. Additionally, CO combines with the incoming O_2 in the combustion to generate CO_2 .

Figure 14 shows that CO exhaust emissions increase with the addition of the HT-FRD mass ratio, indicating that combustion is less efficient so that some of the fuel is not completely burned in each zone. The characteristics of coal fuel are high carbon, energy density, and combustion temperature. Meanwhile, oil palm fronds with lower carbon and energy density, as well as varying combustion quality, are one of the causes of combustion instability in co-firing. Also, uneven air distribution causes some of the fuel to not receive enough oxygen, so the combustion gas is not completely oxidized to CO_2 before leaving the combustion zone, and more CO is produced.

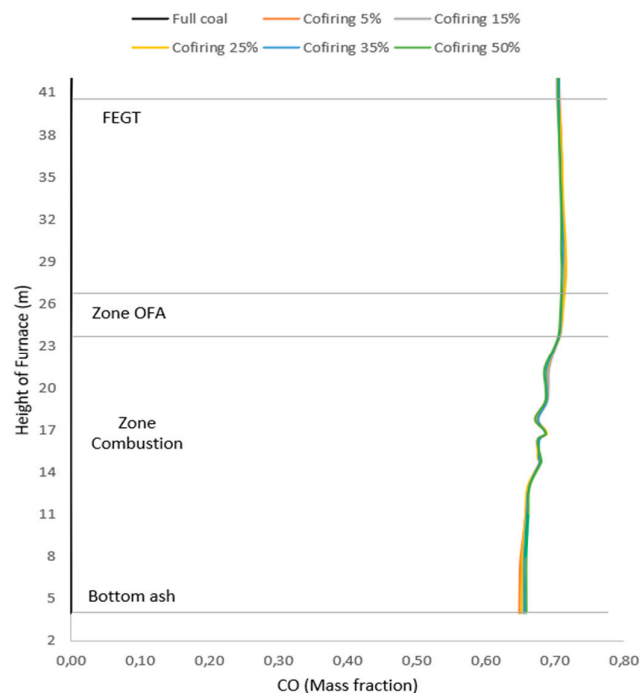


Figure 14. CO distribution at the center across the height of HT-FRD co-firing combustor ratios.

Figure 15 depicts the oxygen distribution profiles within the combustion chamber when co-firing at different HT-FRD ratios. An increased HT-FRD mass ratio leads to a reduction in oxygen concentration. Due to its higher oxygen content relative to coal, HT-FRD can be depleted alongside other flue gasses during combustion. The O_2 concentration exiting the combustion chamber at FEGT increased for HT-FRD co-firing ratios of 0%, 5%, 15%, 25%, 35%, and 50% by 0.042, 0.084 (100% increase), 0.077 (83% increase), 0.075 (78.6% increase), 0.071 (69% increase), and 0.062 (47.6% increase), respectively.

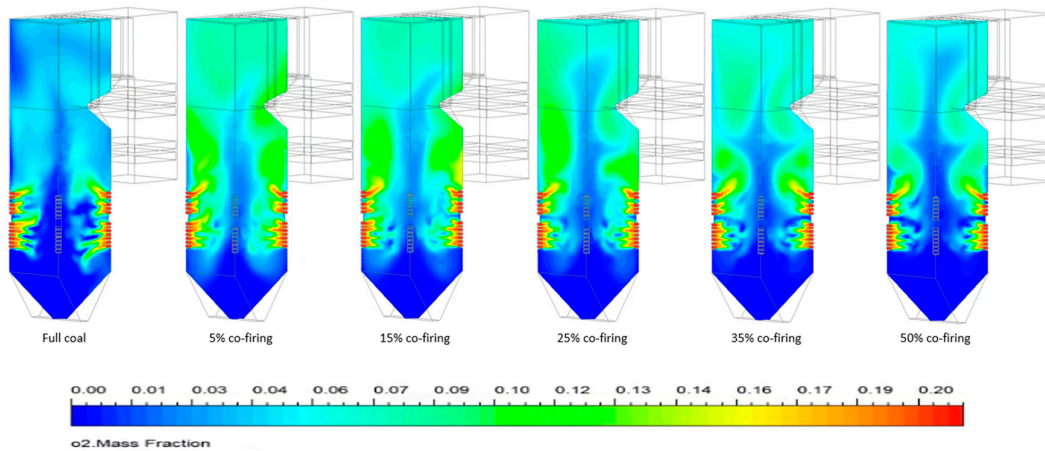


Figure 15. O_2 cross-sectional distribution across the HT-FRD co-firing combustor ratios.

Figure 16 depicts the O_2 concentration curves as they move through the furnace during co-firing, with varying HT-FRD mass ratios.

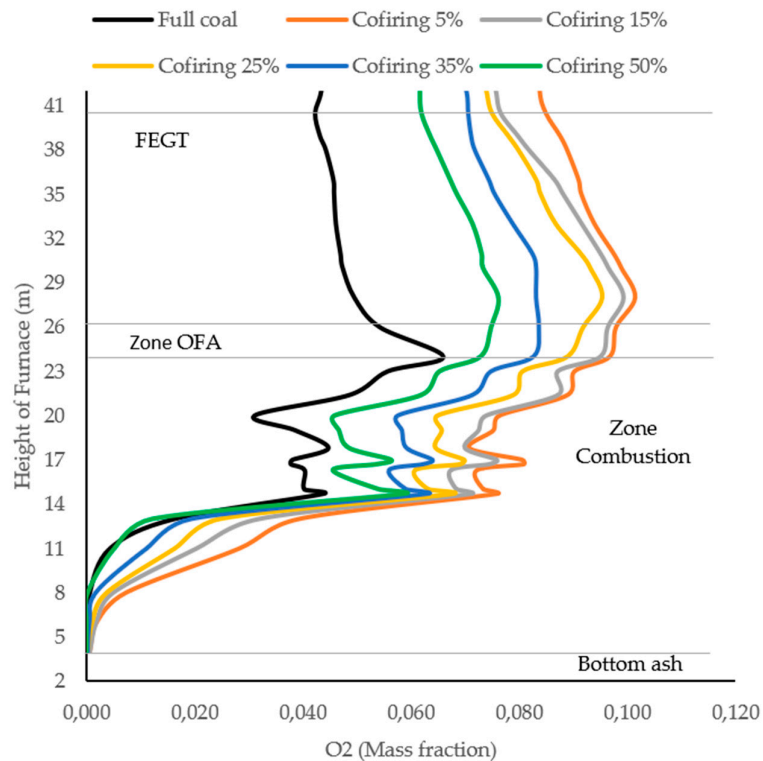


Figure 16. O_2 distribution at the center across the height of HT-FRD co-firing combustor ratios.

In every instance, higher concentrations of O₂ are seen close to the OFA zone, but they diminish gradually as the combustion reaction progresses. When comparing pure coal combustion to HT-FRD fuel combustion, it is observed that HT-FRD fuel can be decomposed quickly, and the combustion produces high temperatures. Therefore, co-firing HT-FRD fuel can increase the consumption of oxygen concentration and reduce the amount of O₂ remaining in the combustion zone. The overall rise in the proportion of O₂ during combustion is mostly attributed to the reduction in the amount of leftover fuel, resulting in a drop in combustion intensity and thus leaving a greater amount of O₂ unused.

7. Conclusions

This study investigated the potential of utilizing advanced FRD as a renewable energy source. Through modeling and evaluating the coal co-firing performance with HT-FRD and using CFD analysis at various mixture mass ratios, it was found that a 5% HT-FRD mass ratio is the most optimal co-firing condition corresponding to the coal-fired power plants' actual conditions. It can be seen from the increase in combustion temperature in the FEGT zone by 10% from 1306 K to 1457 K, the velocity distribution increase by 80%, and the O₂ concentration increase by 100% from 0.042 to 0.084 mf. Most importantly, it can reduce CO₂ emissions by 30%, from 0.187 to 0.130 mf, in the resulting exhaust gas. However, the addition of HT-FRD resulted in a relatively high concentration of CO gas, which means less efficient combustion, meaning that some of the fuel was not completely burned in each zone. This is attributed to the higher volatile matter HT-FRD content compared to coal. Incorporating this natural resource (FRD) can enhance the efficiency of utilizing renewable resources, mitigate environmental impacts, and prolong the operational lifespan of existing and future coal-fired power plants.

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Abbreviations

CFD	computational fluid dynamics
CO ₂	carbon dioxide
CO	carbon monoxide
FEGT	furnace exit gas temperature
HT-FRD	hydrothermal palm frond
OFA	overfire air
O ₂	oxygen
RANS	Reynolds-averaged Navier–Stokes
PA	primary air
SA	secondary air
WSGGM	weighted sum of gray gasses model

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