



Computational Prediction of Co-firing with Various Biomass Waste using Turbulent Non-Premixed Combustion

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ARTICLE INFO

Article history:

Received 4 July 2024

Received in revised form 10 August 2024

Accepted 9 September 2024

Available online 31 October 2024

Keywords:

Biomass waste; coal; co-firing; drop tube furnace; non-premixed combustion; the Probability Density Function

ABSTRACT

Co-firing in coal power plants has limitations because the existing combustion systems are designed to provide optimal performance only with coal. Therefore, investigating the combustion aspects of co-firing by mixing coal with biomass before applying it to existing coal power plants is necessary. To address this, a new numerical model was developed to predict the co-firing behavior of coal with various types of biomass waste, specifically focusing on temperature and pollutant behavior. This study developed a co-firing model in a Drop Tube Furnace (DTF) using a composition of 25% Wood Chips (WC), 25% Solid Recovered Fuel (SRF), 25% Empty Fruit Bunch Fibers (EFFR), and 25% Rice Husk (RH). A structured grid arrangement and the Probability Density Function (PDF) were utilized to depict the relationship between chemical combustion and turbulence. The distributions of temperature and mass fractions of pollutants along the furnace axis were predicted. The highest temperature was observed with 25% EFFR, attributed to its highest volatile matter content. The simulation predicted that 25% RH would be the lowest SO₂ emitter. However, it also showed a slight increase in NO and CO levels due to the increased oxygen content when coal was mixed with biomass. The simulation with 25% EFFR predicted a decrease in CO₂ emissions compared to other biomass types. The results of this parametric investigation could support the implementation of biomass co-firing technology in existing coal-fired power plants.

1. Introduction

Sustainable development relies heavily on renewable energy, although most of the world's energy needs are still met by fossil fuels. Currently, renewable energy sources require significant improvements to compete with the dominance of conventional fuels [1]. Among these sources, biomass emerges as a sustainable and viable substitute for non-renewable energy. Various types of waste, including agricultural and forestry residues, can be converted into electricity and heat [2].

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<https://doi.org/10.37934/cfdl.17.4.89106>

Utilizing biomass as fuel significantly reduces emissions and leverages the abundant availability of biomass [3-6]. In 2019, it was estimated that the capacity of biomass resources in Indonesia reached 37.7 GW. Notably, using oil palm plantation waste alone has the potential to produce around 13 GW of energy [7]. Therefore, biomass offers a promising opportunity to increase the ratio of renewable energy use in Indonesia.

Pulverized coal is a popular method for generating energy in most industries, but it significantly pollutes the air [8]. Most power plants in Indonesia rely on pulverized coal combustion, with the concept of co-firing still in its early stages of implementation [9]. Co-firing biomass offers several advantages. Portions of coal can be substituted with biomass fuels, which are carbon-neutral or even carbon-negative, thus reducing greenhouse gas emissions such as carbon dioxide (CO₂). This substitution can help mitigate climate change and assist in meeting emission reduction targets. Additionally, co-firing can improve overall combustion efficiency and heat outputs, leading to better energy conversion and decreased fuel usage. Biomass waste streams that were previously discarded or left unused can be repurposed, providing an economical means to develop the biomass industry and create new markets for producers. By diversifying the energy sector through co-firing, price volatility can be reduced, and energy security enhanced. Hence, co-firing presents multidimensional benefits [10-14].

However, biomass co-firing has its limitations. One significant concern is the steadiness of biomass feedstock supply [15-16]. Co-firing projects also require supportive policies, incentives, and regulations to be effectively implemented [17-18]. Additionally, biomass feedstocks differ from coal in parameters such as moisture content, particle size, and calorific value. These differences pose challenges in achieving a stable and homogeneous fuel mixture with coal, affecting combustion efficiency, emissions, and plant performance [19-23]. Biomass ash contains higher amounts of alkali and chlorine, leading to equipment corrosion and fouling [24-27]. Consequently, co-firing biomass with coal necessitates modifications to the existing infrastructure of power plants or industrial boilers to accommodate the differing fuel properties. Therefore, research should aim to define the combustion characteristics of co-firing more clearly. This can be accomplished through relatively low-cost and accurate combustion simulation calculation.

The development of numerical simulation methods has made it possible to obtain detailed information on the combustion of pulverized coal and predict the behavior of combustion and pollution. Investigations using the Kobayashi and kinetics/diffusion-limited rate models, along with Computational Fluid Dynamics (CFD), have shown promising results in reducing NO_x and CO₂ emissions during co-firing combustion [28]. Numerical studies on co-firing with torrefied biomass have significantly lowered CO₂ and NO_x emissions [29]. However, as the proportion of biomass co-firing increased, CO₂ emissions rose while SO₂ emissions declined, indicating a reduction in harmful gas emissions and more complete combustion within the furnace [30]. Experiments and numerical studies of co-firing systems with woody biomass have demonstrated effective CO₂ emission reductions at sufficient co-firing ratios [31]. A study using CFD to analyze the combustion of hydrothermally treated empty fruit bunches (HT-EFB) as a coal replacement in existing coal-fired power plants predicted improved combustion performance and emissions reduction [32]. Another study investigated NO_x and SO_x emissions reduction by co-firing mixed coal with corn, wheat, and soybean biomass in tangentially fired boilers at partial boiler loads [33]. These studies aim to guide biomass co-firing practices to reduce unburned carbon, thereby mitigating the threat of spontaneous biomass combustion while ensuring stable furnace combustion and efficient boiler operation [34]. However, these studies require considerable combustion reaction data and computational resources.

The Probability Density Function (PDF) model is reasonably practical and accurate because it directly translates species transport equations [35-36]. Using the PDF model, a numerical study

utilizing a plasma system was conducted to simulate the flow inside a vent during coal combustion and ignition [37]. Research on the characteristics of burning fine coal indicated that introducing steam to the oxidizing mechanism inhibits the creation of NO_x, and the rate at which coal is injected also influences NO_x formation [38-40]. Another study developed multivariate regression models to predict the ignition temperature of pulverized coal [41-43]. An axisymmetric approach for the case of pulverized coal combustion indicated the strong effect of radiative heat transfer; this approach exhibited excellent agreement between the simulation results and the experimental data, primarily because the source term for the particles was highly significant [44]. The PDF model for the study of NO_x emissions within a model of pulverized coal combustion used a computational model [38, 45-48]. The results of a few gases demonstrated that this oxidizer dilution model was suitable for practical combustion system conditions [23].

The model further integrates flamelets generated by non-premixed gaseous flames with the mixture fraction variance transport equation, and the PDF method is used to model the interaction between turbulence and chemistry [49]. A numerical study of pulverized coal in a corner-fired furnace was conducted using the non-premixed MF-PDF combustion model to explore NO reduction in a fuel-rich environment, comparing findings under atmospheric and low-temperature cases [50]. This study addressed non-premixed pulverized coal combustion, considering turbulent gas flow alongside coal particle motion, and included the MF-PDF to model the non-premixed combustion of coal. The study reported that coal powders positively impact combustion efficiency [51].

Co-firing biomass with coal offers many advantages, such as lower greenhouse gas emissions and the utilization of biomass waste streams. However, it has drawbacks related to handling biomass, which has different properties compared to coal, and the need for appropriate modifications of existing power plants or industrial boilers. Previous studies have indicated promising results for reducing pollutants with CFD models, though these studies are often costly in terms of data and computation. Most have been confined to the interaction of coal and the oxidizer, without considering the characteristics of the different types of biomass available in Indonesia.

The present study is necessary because accurate and economically viable computational studies are needed to predict the combustion characteristics and pollutant emissions of co-firing coal with various biomass wastes typical of Indonesia. Using the Probability Density Function (PDF) model to simulate the interaction between turbulence and chemical reactions, this research will provide detailed insights into temperature and pollutant distributions during co-firing. Such information is vital for optimizing co-firing processes, reducing greenhouse gas emissions, enhancing efficiency, and ensuring overall sustainability in energy production in Indonesia.

Computational fluid dynamics (CFD) combustion simulations examined the impact of various biomass waste materials when co-firing with bituminous coal. A detailed study was conducted on the characteristics of biomass available in Indonesia that can be utilized as co-firing solid fuel. The materials selected are the most common biomass waste produced in Indonesia, which includes mixed empty fruit bunches and fronds from palm oil trees (EFFR), rice husk (RH), solid recovered fuel from municipal waste (SRF), wood chips (WC), and Kalimantan coal. The co-firing simulation model was adapted from a drop tube furnace (DTF) [52]. The main objective of this study is to estimate the combustion temperature and pollutants produced during co-firing

2. Models and Methods of Numerical Simulation

2.1 DTF and Geometry

The Drop Tube Furnace (DTF) combustion furnace dimensions are used to adopt a structured mesh for the CFD simulation domain in the ANSYS Fluent program. According to *Hariana et al.*, [52–

54], the simulation parameters adopted those used in the DTF test. The DTF has been selected as it can simulate combustion under boiler conditions [53]. The DTF is a cylindrical ceramic tube of radius 0.035 m and length 1.2 m working of temperature 1200°C and air-fuel ratio of 1:7. The geometry and dimensions of the DTF are shown in Figure 1. Axisymmetric allows for simplifying three-dimensional problems into two dimensions, significantly reducing the computational effort.

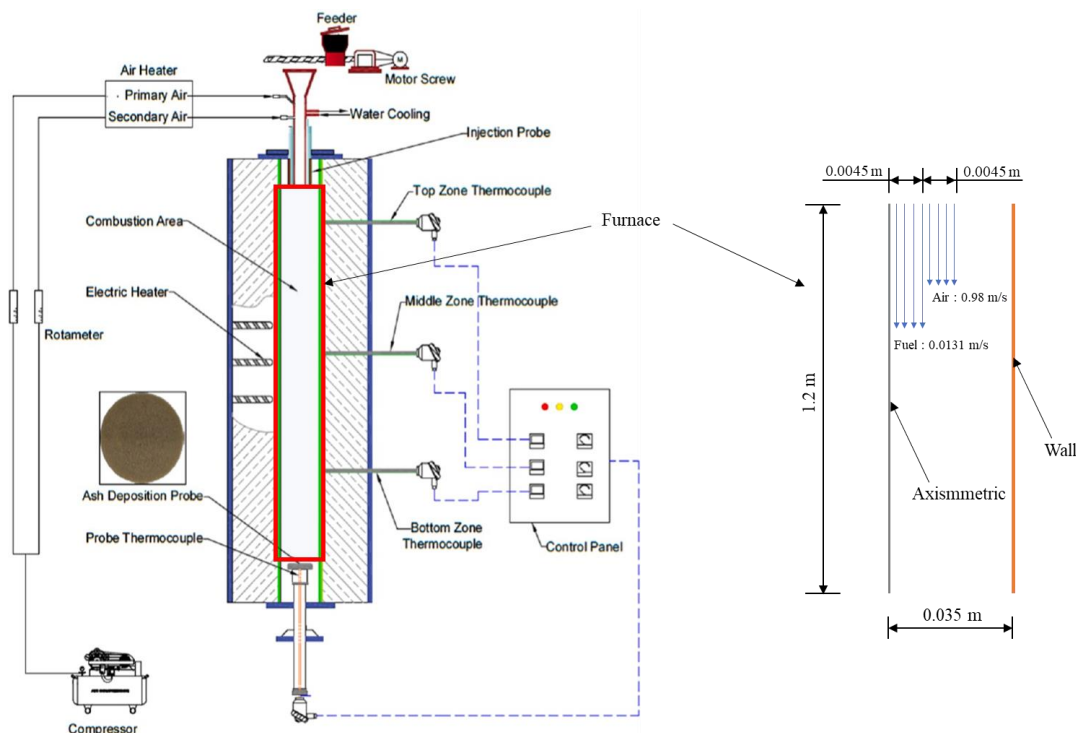


Fig. 1. DTF [52-54] and domain of CFD

Table 1
 Proximate and ultimate analysis [52]

Parameter	Coal	25% WC	25% RH	25% EFFR	25% SRF
Proximate					
Inherent Moisture	0.0934	0.0897	0.0861	0.0833	0.0807
Ash Content	0.0688	0.0577	0.1044	0.057	0.126
Volatile Matter	0.397	0.4755	0.4526	0.4975	0.4344
Fix Carbon	0.4408	0.3772	0.3568	0.3621	0.3589
Ultimate					
Carbon	0.6624	0.6121	0.5794	0.6024	0.578
Hydrogen	0.0443	0.0463	0.045	0.0474	0.0438
Nitrogen	0.0137	0.0114	0.0112	0.0114	0.0146
Sulfur	0.006	0.0047	0.0045	0.0046	0.0057
Oxygen	0.2048	0.2678	0.2555	0.2772	0.2319

Indonesian waste coals and biomass, including bituminous coal from East Kalimantan, were used. The EFFR was a mixture of EFB and FRD of palm oil trees from Banten, with a mixture composition of 50% EFB and 50% FRD. WC from Central Java, RH from West Java, and SRF from municipal waste in Banten. The diameter for all biomass samples was 250µm. The conditioned coal was mixed with each

biomass in a 75% coal and 25% biomass ratio. The ultimate and proximate analyses of the coal and mixture samples in this model are indicated in Table 1 [52].

2.2 Mathematical Models

The governing equations of CFD used in this model [36, 55-56]:

Continuity equation:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{u}) = 0 \quad (1)$$

Momentum equation:

$$\frac{\partial}{\partial t} (\rho \vec{u}) + \nabla \cdot (\rho \vec{u} \vec{u}) = -\nabla p + \nabla \cdot (\bar{\tau}) + \rho \vec{g} \quad (2)$$

The energy equation:

$$\frac{\partial}{\partial t} (\rho H) + \nabla \cdot (\rho \vec{u} H) = \nabla \cdot \left(\frac{k_t}{c_p} \nabla H \right) + S_h \quad (3)$$

S_h is the source of chemical reaction energy:

$$S_h = -\sum \frac{h_j^0}{M_j} R_j \quad (4)$$

H is the total enthalpy:

$$H = \sum_j Y_j H_j \quad (5)$$

The equation used to transport turbulent kinetic energy (K) and turbulent effects were considered by utilizing the k - ε turbulent model [57] Table 2 shows the model constants of the k - ε turbulent model. is as follows:

$$\frac{\partial (\rho k)}{\partial t} + \nabla \cdot (\rho \vec{u} k) = \nabla \cdot \left[\left(\mu + \frac{\mu_t}{\sigma_k} \right) \nabla k \right] + G_k - \rho \varepsilon + P_K \quad (6)$$

Table 2
Model constants of the k - ε turbulent model [58]

C_μ	σ_k	σ_ε	C_1	C_2	η_0	β	K
0.0845	1	1.3	1.42	1.68	4.38	0.0012	0.41

The Discrete Ordinates (DO) model [59].

$$\nabla \cdot (I_\lambda(\vec{r}, \vec{s})\vec{s}) + (a_\lambda + \sigma_s)I_\lambda(\vec{r}, \vec{s}) = a_\lambda n^2 I_{b\lambda} + \frac{\sigma_s}{4\pi} \int_0^{4\pi} I_\lambda(\vec{r}, \vec{s}') \varphi(\vec{s}, \vec{s}') d\Omega' \quad (7)$$

Discrete Phase Model (DPM) trajectory coal:

$$m_p \frac{d\vec{v}_p}{dt} = \Sigma \vec{F} \quad (8)$$

\vec{F} is an external force. The dominant forces that affect the particle are drag and buoyancy forces. This leads to a specific equation of motion [60].

$$\frac{g(\rho_p - \rho)}{\rho_g} \frac{d\vec{v}_p}{dt} = F_D(\vec{v} - \vec{v}_p) + \frac{g(\rho_p - \rho)}{\rho_g} \quad (9)$$

Re_p describes the particle Reynolds number, while C_D represents the Drag coefficient [60]:

$$Re_p = \left(\frac{\rho d_p |\vec{v}_p - \vec{v}|}{\mu} \right) \quad (10)$$

$$C_D = \frac{24}{Re} (1 + 11.2355 Re^{0.653}) + \frac{(-0.8271) Re}{8.8798 + Re} \quad (11)$$

Devolatilization [57]:

$$\frac{-dm_p}{dt} = k(m_p - (1 - f_{v,0} - f_{w,0})m_{p,0}) \quad (12)$$

Where:

$$k = A_1 \exp\left(\frac{-\varepsilon}{RT}\right)$$

The Mixture Fraction and PDF Modeling [57]:

Mean mixture fraction \bar{f} :

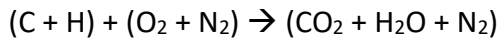
$$\frac{\partial(\rho\bar{f})}{\partial t} + \nabla \cdot (\rho\bar{f}\vec{u}) = \nabla \cdot \left(\frac{\mu_t}{\sigma_t} \nabla \bar{f} \right) + \frac{\dot{m}_{p,0}}{m_{p,0}} (m_{p,in} - m_{p,out}) \quad (13)$$

Mean mixture fraction variance (\bar{f}'^2):

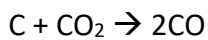
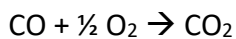
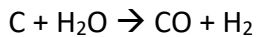
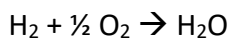
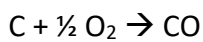
$$\frac{\partial(\rho\bar{f}'^2)}{\partial t} + \nabla \cdot (\rho\bar{f}'^2\vec{u}) = \nabla \cdot \left(\frac{\mu_t}{\sigma_g} \nabla \bar{f}'^2 \right) + 2.86\mu_t (\nabla \bar{f}'^2) - 2\rho \frac{\varepsilon}{k} \bar{f}'^2 \quad (14)$$

There are three primary ways in which NOx can be produced during combustion [61]. These possess the thermal of NO, the prompt of NO, and the fuel-bound of NO, all of which interest

atmospheric oxidation [62]. Despite the actual mechanism, the two primary pathways of NOx formation still need to be understood entirely. First, oxidation is transient nitrogen species in the initial steps, where nitrogen reacts with other essences to form intermediate products that finally lead to NO. Under loosening requirements, the nitrogen transforms into N₂ gas, partially forming NOx. The second pathway involves the char matrix of the fuel during combustion. This process appears more gradually than the first pathway. The nitrogen of char is eventually transformed into NOx. The NOx constructed decreased back to nitrogen by the char in its carbon form [61]. The procedure of combusting co-firing can be described as follows:



And other reactions:



The pulverized co-firing combustion using the Nusselt number for inert heating has been considered [36]:

$$Nu = \frac{hD}{k} = 2 + 0.6Re^{1/2}Pr^{1/3} \quad (15)$$

The solid fuel relaxation time considerably surpassed the turbulence time scale, and large particles affected by the turbulence fluctuation velocity decreased. The PDF integrates the powerful consequence of turbulence on the chemical reaction.

2.3 Numerical Procedure and Boundary Conditions

ANSYS Fluent is utilized to simulate the flow of various substances and solve the partial differential equations that govern these flows. All convective terms are resolved using the QUICK method, while the velocity is determined using the SIMPLE algorithm. Turbulence and chemistry are simulated using the PDF method to solve a single transport equation [38, 45-47]. The computation process terminates when the residual values for all equations fall below a threshold of 10⁻⁷.

The specified inlet velocity of the furnace is adjusted according to the air-fuel ratio and wall conditions to address issues in the non-adiabatic system. The furnace walls are maintained at 1200°C, with isothermal boundary conditions set to simulate DTF conditions. The 2D model simulates only half of the furnace, with the centerline subjected to axisymmetric conditions. An outflow condition is applied at the DTF outlet. Referring to *Hariana et al.*, [52-54], the DTF specification used as a calculation domain can be seen in Figure 1.

2.4 Validation

The accuracy of the grid resolution significantly impacts the quantitative results. Once the computational domain is refined beyond a certain level, further adjustments do not lead to substantial quantitative deviations, achieving mesh independence [63]. The computational area is divided into structured sections. Figure 2(a). presents a two-dimensional structured mesh rectangle depicting the Drop Tube Furnace (DTF). Figure 2(b) shows a section of the mesh, illustrating that all parts of the geometry have a structured mesh of the same size.

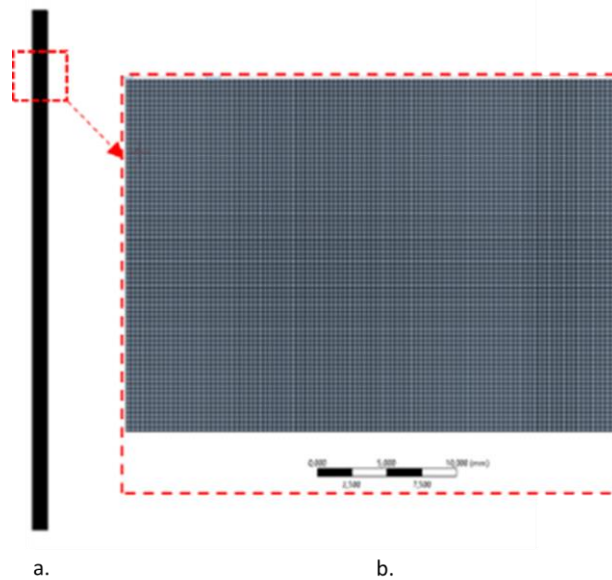


Fig. 2. (a) Full body mesh and (b) Structured mesh

The grids were structured with varying cell counts of 44437, 89700, 180164, and 367120 cell counts. The increase in cell counts was two times the number of cells, then tested to examine the mass fraction of CO_2 along the furnace axis. The outcomes were estimated, and the computational grid structure that exhibited no alteration in CO_2 along the furnace axis with increasing refinement was chosen for in-depth analysis. This specific grid underwent a grid independence test to ensure its reliability. Figure 3 shows the CO_2 profile of combustion of 100% coal in the furnace center for different cell counts, and the fourth grid was selected for all simulation scenarios to ensure greater confidence.

The coal combustion simulation using the fourth grid was compared with a simulation study of coal combustion in a DTF using a two-step global mechanism conducted by *Darmawan et al.*, [64], as explained in Figure 4. The current combustion model with the selected number of cells was also compared with experimental data. The simulation results of the current model are in reasonable agreement with the observed data

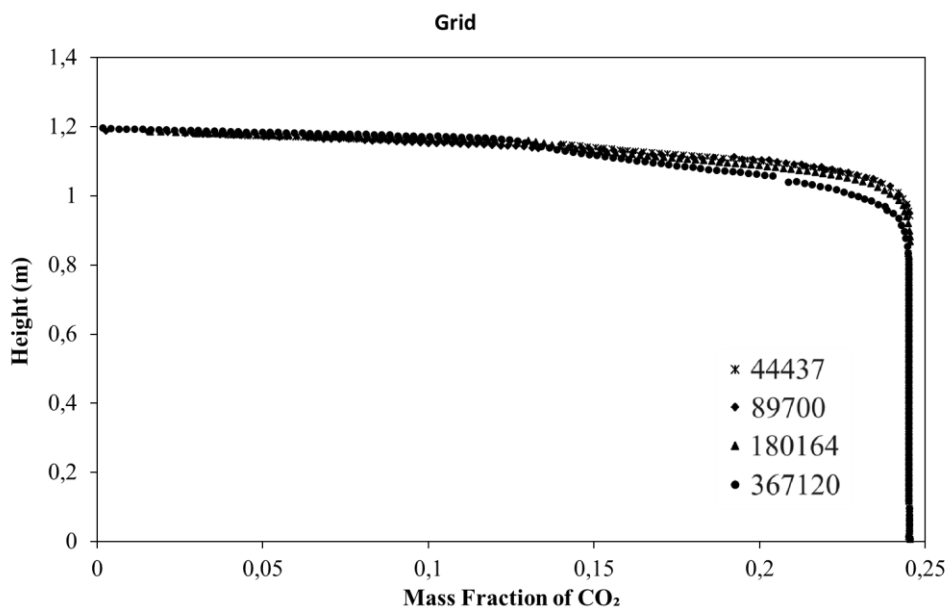


Fig. 3. Mass fraction of CO₂ in various numbers of cells

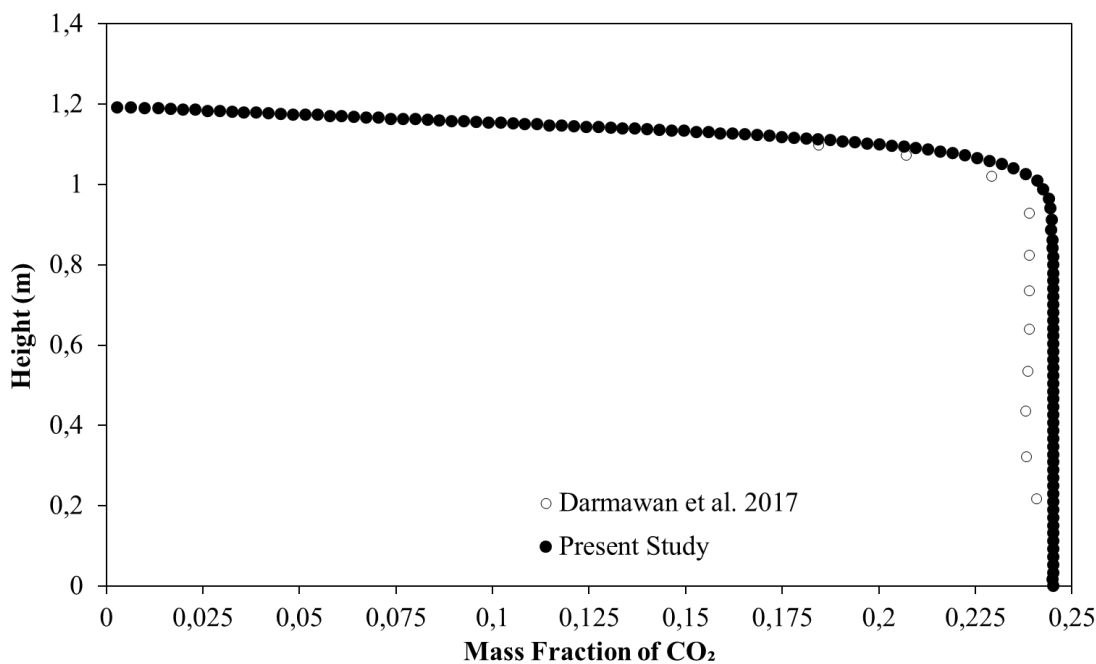


Fig. 4. Comparison of mass fraction CO₂ from coal with the work of *Darmawan et al.*, [64]

3. Result and Discussion

The numerical study of pulverized co-firing combustion in a 2-D Drop Tube Furnace (DTF) with various biomass wastes was investigated. Figure 5 depicts the temperature contour along the furnace and the temperature graph relative to the distance from the furnace inlet along the furnace axis during the firing process. The highest combustion temperature was observed with 25% EFFR, while the lowest was recorded with coal. The difference in combustion temperature is noticeable from the inlet at the height of 1.2 m to 0.6 m due to fuel combustion. Then, it becomes uniform towards the outlet domain as the fuel is completely burned out.

Several factors can cause temperature increases in co-firing combustion. Firstly, biomass has higher reactivity than coal and contains volatile organic compounds that quickly release combustible

gases when heated [65]. Table 1 shows the enormous amount of volatile matter in 25% EFFR, and the order of highest to lowest temperature follows Figure 5. Additionally, biomass fuels have lower ash content compared to fossil fuels. Ash has a higher heat capacity, which can cause the combustion process in biomass co-firing to reach higher temperatures [66-68]. Co-firing combustion also increases the combustion air supply to ensure proper mixing and combustion of biomass and fossil fuel. The increased airflow provides more oxygen to support combustion, leading to higher temperatures [11, 69]. A synergistic effect occurs in co-firing, where combining both fuels improves the overall combustion process. This can influence the combustion characteristics of fossil fuels, promoting more efficient and complete combustion and producing higher temperatures [70-73].

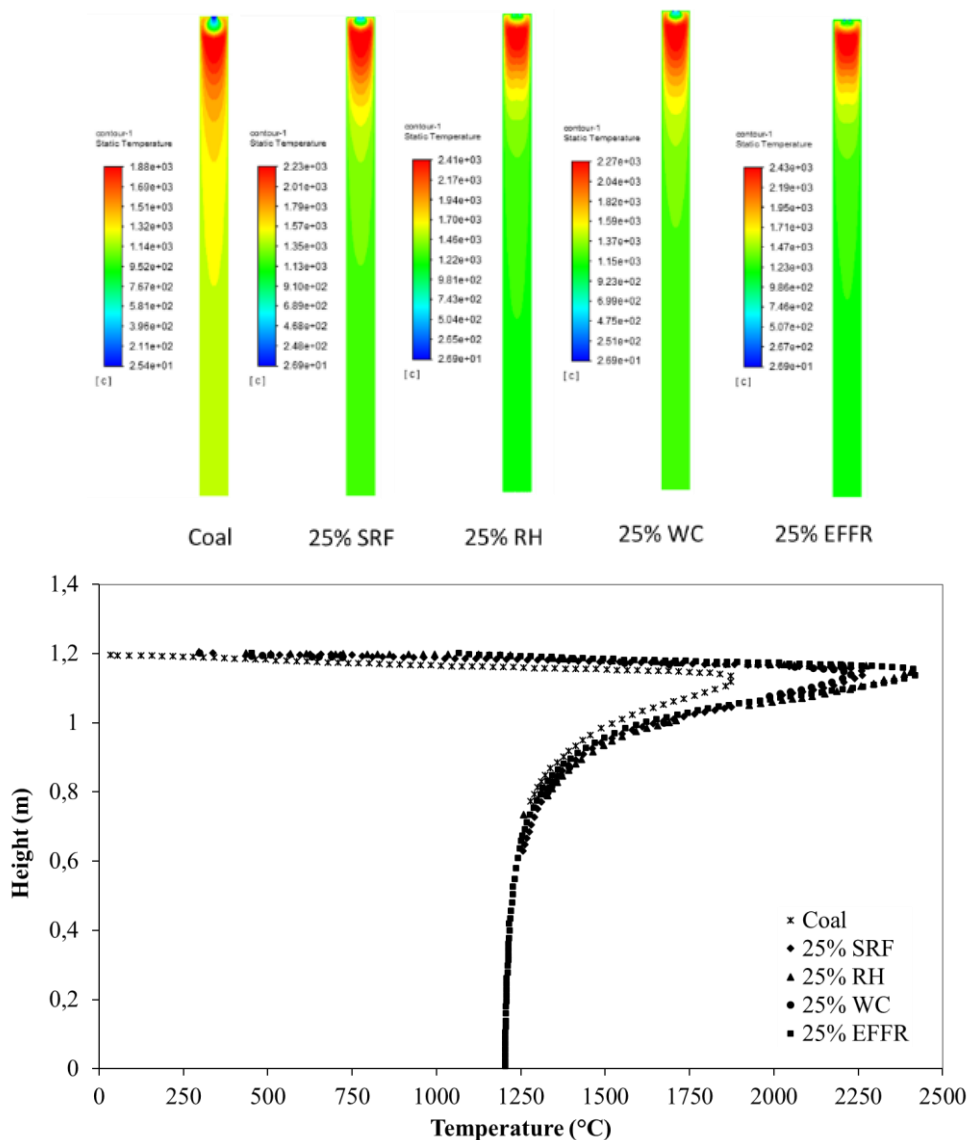


Fig. 5. Comparison of the temperature

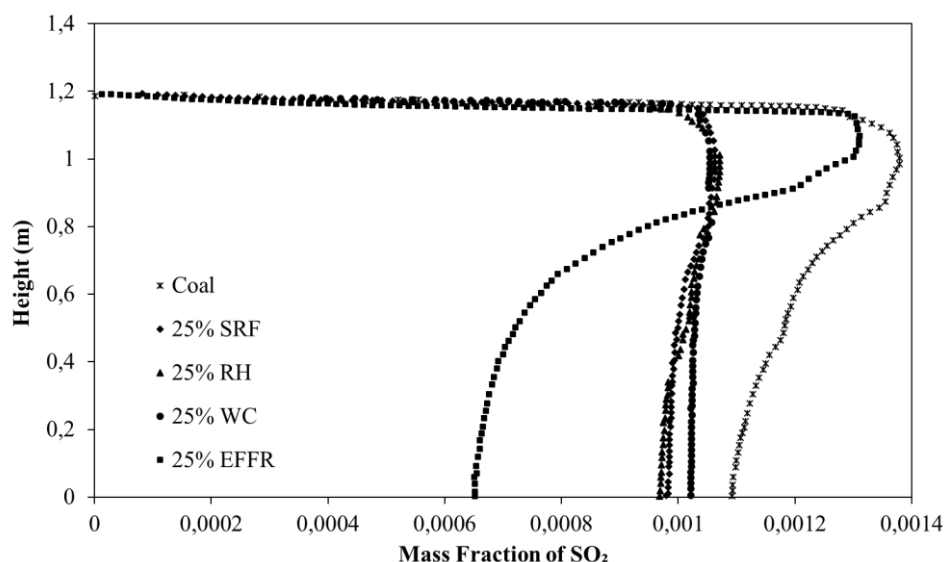


Fig. 6. Comparison of the SO₂

Coal has a significant sulfur content due to organic sulfur and pyrite [74]. Figure 6 shows that the highest SO₂ content was observed in 100% coal combustion, as sulfur in coal naturally converts to sulfur dioxide during combustion. The mass fraction of SO₂ in 25% SRF was unique. At the beginning of the combustion process, SO₂ levels were the highest compared to other biomass types. However, after one-third of the function, it decreased significantly and was lower than other biomass types. This may be due to the multi-component nature of SRF causing significant changes. The lowest SO₂ content was found in 25% RH combustion. The low sulfur content of biomass can reduce the sulfur emissions from coal in co-firing [75-78].

Biomass contains sulfur capture agents such as alkali metals (potassium, sodium) and calcium that can react with sulfur compounds during combustion. These agents result in non-volatile compounds, such as sulfate and sulfide, which are less likely to be released as SO₂ [74]. The co-firing of coal and biomass presents an effect of synergy on sulfur capture. It can influence combustion conditions, such as temperature and residence time, to enhance the sulfur capture mechanism. Additionally, biomass ash can interact with coal ash, forming clumps that effectively capture sulfur compounds [70-73].

Figure 7(a) explains the prediction of CO mass fraction at each biomass and coal, showing 25% EFR has the largest CO and coal has the lowest. CO increases in combustion because of the oxygen content in the fuel. Table 1 displays the percentage of oxygen in the fuel, of which 25% EFR has higher oxygen content than others. Figure 7(b) depicts mass fraction NO that has similar CO characteristics. The generating NO phenomenon heavily relies on the flame temperature because thermal NO_x is generated through chemical reactions that occur when oxygen and nitrogen during combustion produce nitrogen oxides, which is comprehended as the Zeldovich mechanism [79-82].

Besides, biomass generally contains more nitrogen than fossil fuels [83]. When combusted, nitrogen in biomass reacts with oxygen in the air and forms nitrogen oxides (NO_x), mainly NO. As a result, the increased nitrogen content of biomass leads to higher NO emissions than coal. Biomass fuels generally have a complex composition and possibly a higher moisture content than coal [84]. Water vapor influences combustion by leading to incomplete combustion, which would result in higher carbon monoxide (CO) release.

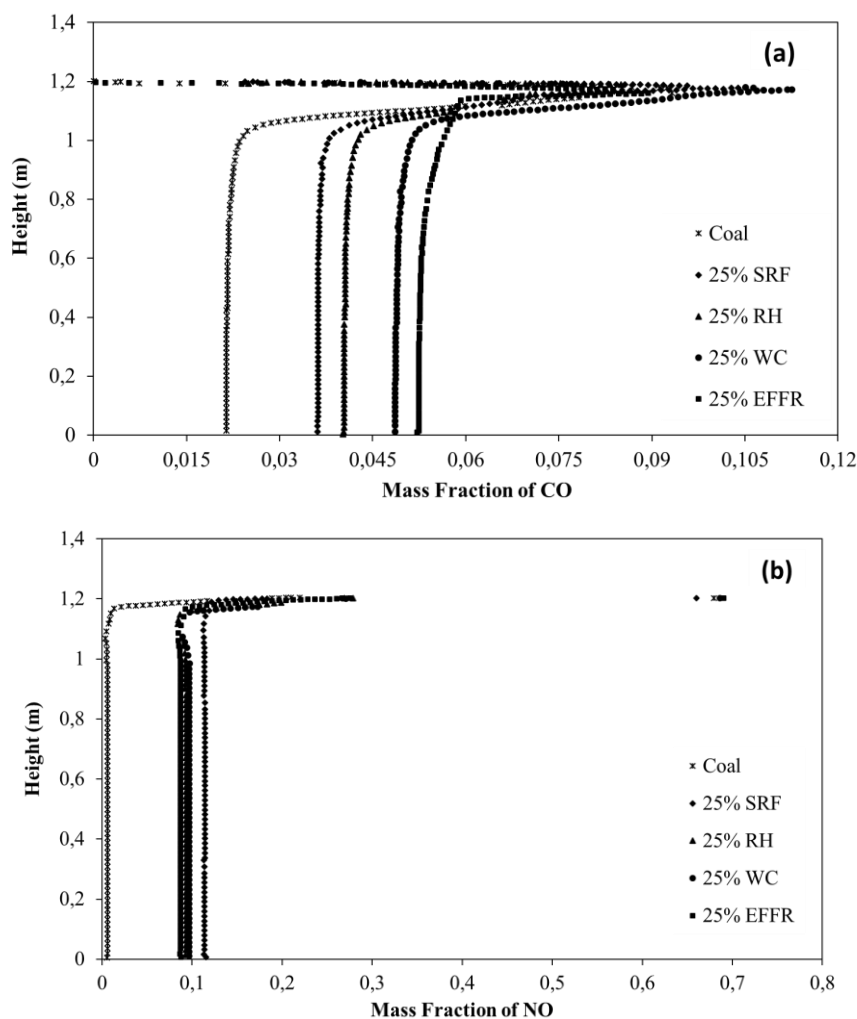


Fig. 7. (a) Mass fraction CO and (b) Mass fraction NO

The combustion of biomass with fossil fuels may change the combustion environment within the furnace. Biomass typically possesses a low heating value and different combustion features than fossil fuels. The differences can affect the mixing and residence time of fuel and air, resulting in incomplete combustion and increased emission of CO and NO [21, 72]. Despite the increased SO₂ and NO emissions in the co-firing combustion simulation, they remain below the regulatory standards of 200 mg/Nm³ [85].

Figure 8 shows the CO₂ pollutant mass fraction, and biomass co-firing produces less CO₂ than coal. The mass fraction of CO₂ significantly reduces due to the 25% EFR, then 25% SRF, 25% RH, and 25% WC. However, 100% of coal combustion has the highest CO₂ emission. The overall emissions of CO₂ are reduced due to using carbon-neutral biomass. Even though some CO₂ is released because of biomass combustion, it does not participate in a long-term increase in the CO₂ level in the atmosphere because it is balanced out by the absorption of CO₂ during the growth phase of the biomass [86-87].

The CO₂ emissions signify that the combustion is complete and may also be responsible for influencing temperature. In an environment rich in fuel but with less excess air, the concentration of CO₂ is improved significantly. The amount of CO₂ generated is directly proportional to the fuel. The rate of CO₂ generation under reducing atmospheres is different. With a limited supply of oxygen, even with twice the amount of fuel, the rate of CO₂ generation falls sharply. It is essential to mention that the overall reduction in CO₂ emissions through biomass combustion depends on several factors,

such as the percentage of biomass used, the nature of biomass, the efficiency of the combustion process, and other associated factors.

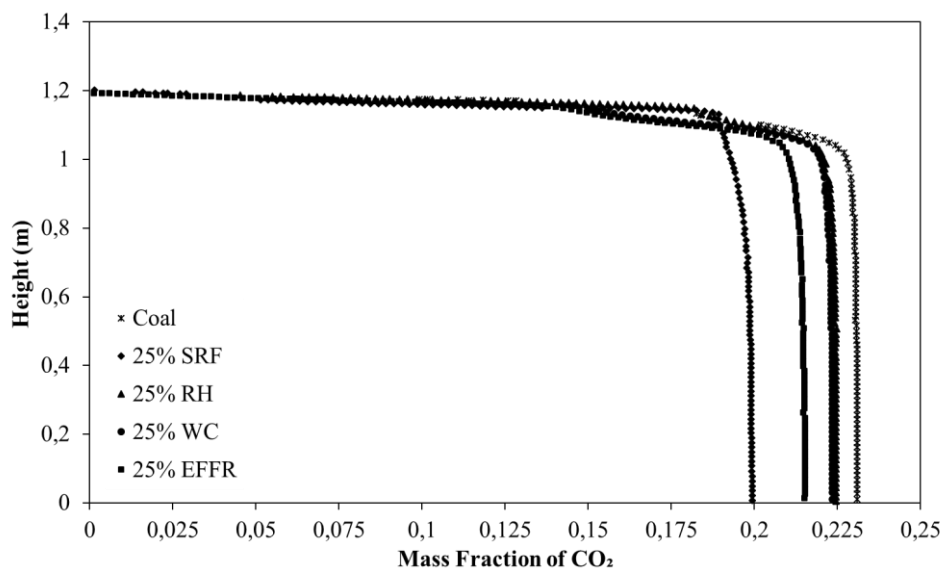


Fig. 8. Mass fraction CO₂

4. Conclusion

A coal and biomass waste co-firing simulation in a 2-D DTF was performed using the mixture of 75% bituminous coal with 25% biomass consisting of 25% WC, 25% RH, 25% EFFR, and 25% SRF. The simulation predicted pollutants and temperature combustion phenomena. As a part of the review, the mass fractions and temperature of CO, NO, and CO₂ are presented in graphical form. Simulation analysis revealed that combustion temperature increases as combustion occurs from the inlet to the midpoint of the DTF furnace and becomes steady. The volatile matter is the most influential biomass mixture in different biomasses at various combustion temperatures. Coal added with biomass increases volatile matter since biomass has a significant volatility, which raises the value when mixed with biomass. The highest combustion temperature among these simulations was the 25% EFFR mixture, which started at 2285°C compared to other biomass mixtures. The lowest was the 100% coal mixture since coal has a lower volatile matter than biomass.

The simulation results also agreed to a reduction in SO₂ emissions while co-firing. The reduction in SO₂ emission was due to the low sulfur content in the biomass fuels. Among all the biomasses tested, RH had the lowest SO₂ emissions. However, a slight increase in the concentration of NO and CO was noticed while co-firing compared to the respective emissions while using coal. This rise was attributed to the high oxygen content in the biomass, but the emissions were still beneath the levels set by Indonesia's environmental regulations. Also, the simulation results showed reduced CO₂ emission while co-firing. In this emission, EFFR showed the most significant reduction in CO₂ emission when it co-fired. The scope for further work is to determine the effect of solid fuel diameter variation and sphericity during co-firing. The study will help ascertain a pulverized boiler's residence time and pollutant production.

Acknowledgments

The researcher expresses gratitude to the National Research and Innovation Agency (BRIN) for their assistance in enabling the research

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