CHEMICAL ENGINEERING TRANSACTIONS
VOL. 120, 2025

A publication of
AIDIC
The Italian Association
of Chemical Engineering
Online at www.cetjournal.it

Guest Editors: Bing Shen How, Viknesh Andiappan, Denny K.S. Ng, Hon Loong Lam, Petar S. Varbanov

ISBN 979-12-81206-21-2; **ISSN** 2283-9216

DOI: 10.3303/CET25120054

Impact of Biomass Co-Firing on Flame Temperature and Pollutant Emissions in a 300 MW Coal-Fired Boiler: A Computational Fluid Dynamics Analysis

Muhammad N. Zulkifle*,Suzana Yusup

Energy Generation, Energy Generation & Materials Unit, TNB Research Sdn. Bhd., 43000 Kajang, Selangor, Malaysia
nuruddin.zulkifle@tnb.com.my

Computational Fluid Dynamics (CFD) is a valuable tool for analysing combustion processes in power generation systems. This study investigates the impact of biomass co-firing on combustion characteristics and emissions in a 300 MW coal-fired utility boiler. Three fuel cases were simulated: 100 % coal, 3 % biomass co-firing, and 10 % biomass co-firing, using empty fruit bunch (EFB) as the biomass component. The simulations applied a non-premixed combustion model along with the SST k-ω turbulence model for accurate treatment of near-wall and high-shear flow regions. Radiative heat transfer was modelled using the discrete ordinates (DO) method. Results showed that co-firing 10 % EFB reduced NOx emissions by 24.5 % (from 511.8 to 386.6 mg/m³) and decreased CO_2 concentration from 11.35 % to 10.45 %. Flame temperature also declined from 1,066.5 °C to 1,034.3 °C, while remaining within safe operating limits. These findings demonstrate the feasibility of low-ratio biomass co-firing for reducing emissions without compromising boiler performance. The CFD approach provides a practical framework for evaluating co-firing strategies, offering technical support for power plant operators aiming to improve environmental performance under existing infrastructure constraints.

1. Introduction

As the world shifts toward low-carbon energy systems, interest in sustainable combustion strategies that can work with existing fossil fuel infrastructure is growing. Biomass co-firing in conventional pulverized coal boilers is a practical and cost-effective option to reduce greenhouse gas emissions while maintaining reliable power generation. Biomass is considered renewable and carbon-neutral over its lifecycle, allowing part of the coal to be replaced without major boiler modifications. However, even small amounts of biomass can affect combustion performance due to its variable and reactive nature.

Co-firing involves complex interactions, including gas-solid flow, turbulence, particle transport, heat and mass transfer, pyrolysis, combustion, and pollutant formation (Wang et al., 2025). Biomass typically has a higher volatile content and begins pyrolysis at lower temperatures than coal, which leads to earlier ignition (Mularski and Li, 2023). At low co-firing ratios, this can influence flame shape and stability, causing uneven heat distribution and potentially higher emissions from incomplete combustion (Chen et al., 2017).

CFD is a valuable engineering tool that helps analyse boiler operation by providing detailed information on flow, temperature, and species distribution—data that is often difficult to obtain experimentally. It offers insight into flame behaviour, emissions, and heat distribution, making it useful for evaluating co-firing strategies (Yao et al., 2025). CFD also allows virtual testing of different fuel combinations, supporting better decisions before changes are made in actual plant operations.

Running accurate CFD simulations depends on more than just fuel input data, it also requires choosing the right models for turbulence, heat transfer, and chemical reactions. Accurate combustion modeling requires careful calibration of simulation parameters, particularly when dealing with mixed fuels such as coal and biomass. Extensive research has focused on high-percentage biomass blends and laboratory-scale experiments, limited attention has been given to the behavior of low biomass ratios in full-scale industrial boilers (Black et al., 2013).

This study uses Computational Fluid Dynamics (CFD) to evaluate the effects of low-ratio biomass co-firing on combustion and emissions in a 300 MW utility boiler. Three fuel cases were analyzed: 100 % coal, 3 % biomass,

Paper Received: 22 May 2025; Revised: 5 September 2025; Accepted: 20 September 2025
Please cite this article as: Zulkifle M.N., Yusup S., 2025, Impact of Biomass Co-Firing on Flame Temperature and Pollutant Emissions in a 300 MW Coal-Fired Boiler: A Computational Fluid Dynamics Analysis, Chemical Engineering Transactions, 120, 319-324 DOI:10.3303/CET25120054

and 10 % biomass co-firing. While previous research has primarily addressed higher biomass blending ratios, often requiring significant system modifications (Sun et al., 2022), this work focuses on lower co-firing levels that are more compatible with existing operational setups. The model integrates verified fuel properties for coal and EFB, detailed furnace geometry, and advanced sub-models for combustion, turbulence, and radiation.

The objective of this study is to evaluate the impact of low-ratio biomass co-firing on flame temperature and pollutant emissions, and to develop a validated CFD-based framework to support informed operational decisions in practical boiler applications.

2. Numerical setup

2.1 Pre-processing

CFD simulations were conducted in ANSYS Fluent to model combustion and emissions in a 300 MW opposed-fired pulverized coal boiler. The geometry represents a full-scale utility boiler with multiple burners and heat exchanger sections, based on the layout of an actual operational unit. As shown in Figure 1, pulverized fuel mixed with primary air (PA) and secondary air (SA) was injected through five mills (A–E), while over-fired air (OFA) was introduced through upper ports to enable staged combustion. The total fuel feed rate was 114 t/h, and the total air input, including PA, SA, and OFA, was 1,498 t/h, distributed across all inlets using mass flow boundary conditions.

A grid independence test was carried out to ensure the reliability and numerical stability of the simulation results. Five mesh densities were evaluated, consisting of approximately 10, 18, 26, 37, and 48 M elements. The maximum flame temperature at the furnace centreline was used as the reference variable for comparison. A progressive reduction in temperature variation was observed with increasing mesh resolution. The difference between the fourth and fifth mesh was found to be less than 0.12 % as shown in Figure 2, indicating that further refinement had negligible influence on the key solution variable. Based on this convergence behaviour, the mesh with 37 M elements was selected as the final computational grid, as it provided a satisfactory balance between simulation accuracy and computational efficiency. Additionally, mesh quality metrics, including skewness (0.124) and orthogonal quality (0.886), remained within acceptable limits, further confirming the suitability of the chosen mesh for resolving the complex flow, combustion, and heat transfer phenomena in the boiler furnace.

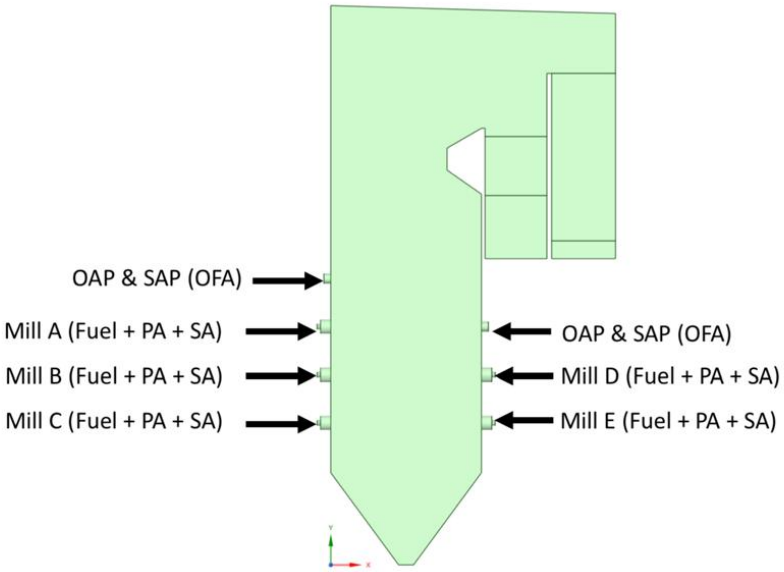


Figure 1: Cross-sectional side view of the 300 MW opposed-fired utility boiler used in the CFD simulation.

The simulations employed a steady-state, pressure-based solver to capture time-dependent combustion behavior under steady full-load conditions. A non-premixed combustion model was used to represent the interaction between the injected solid fuels and oxidizing air, incorporating a probability density function (PDF) approach to model turbulence-chemistry interactions, as suggested by Hafiz et al. (2018). Turbulence was modeled using the SST k-ω model, selected for its improved accuracy near wall boundaries and in regions of strong shear. Radiative heat transfer was calculated using the discrete ordinates (DO) method, which accounts for directional radiative exchange among combustion gases, solid particles, and furnace walls, as recommended by Gazdallah et al. (2012).

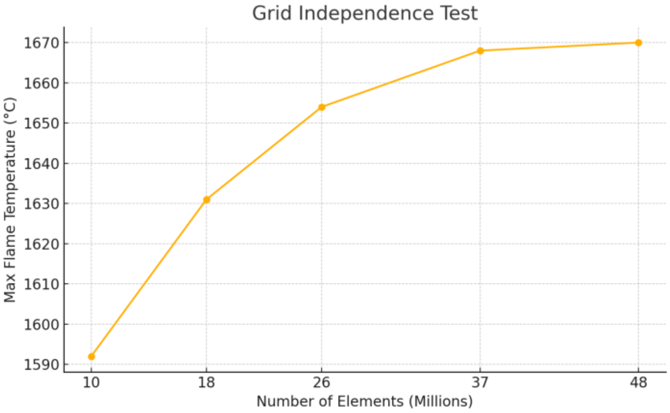


Figure 2: Grid independence test showing negligible variation in maximum flame temperature beyond 37 M elements, confirming mesh convergence.

The solid fuel phase was modeled using a Rosin-Rammler particle size distribution with a mean diameter of 75 µm, representing typical pulverized coal and biomass sizes used in industrial-scale burners (Bach et al., 2014).

2.2 Cases

To evaluate the impact of biomass blending, three fuel scenarios were developed:

- Case A: 100 % Coal A (baseline)
- Case B: 97 % Coal A + 3 % EFB Biomass
- Case C: 90 % Coal A + 10 % EFB Biomass

The three fuel cases were selected to reflect both current co-firing practices and the potential for increased biomass utilization without significant modifications to existing boiler infrastructure. Case A (100 % coal) served as the reference scenario, while Cases B (3 % EFB) and C (10 % EFB) introduced incremental biomass blending to evaluate its impact on combustion behaviour and emission performance. The 3 % biomass ratio was based on prior operational testing at a coal-fired power plant in Malaysia, where combustion remained stable and system performance was deemed acceptable. Although large-scale biomass co-firing is not yet widely adopted across Malaysian power stations, this ratio represents a practical and validated starting point for gradual integration. The 10 % co-firing case was included to investigate the feasibility of higher biomass substitution levels within the operational constraints of conventional boiler systems. This range of scenarios allows for a systematic assessment of the thermal and environmental implications of low-ratio biomass co-firing in large-scale utility boilers.

2.3 Solid fuel properties

The simulations used two solid fuels: Coal A and EFB biomass. Coal A is a medium-volatile bituminous coal, suitable for power generation due to its stable combustion and moderate energy content. Empty Fruit Bunch (EFB) is a biomass waste from palm oil processing, widely available in Southeast Asia. It contains high levels of volatile matter and oxygen, which affect how it burns when mixed with coal. The contrasting properties of Coal A and EFB make their combination important to study in co-firing applications, especially for combustion behaviour and emissions.

As shown in Table 1, Coal A has higher fixed carbon and gross calorific value, resulting in stronger flame stability and higher peak temperatures. In contrast, EFB contains more volatile matter, more oxygen, and less fixed carbon, contributing to faster ignition but cooler and more spread-out flames. These differences significantly affect flame temperature, burnout time, and pollutant formation. The lower nitrogen and sulphur content in EFB is also expected to reduce NOx and SOx emissions.

To represent co-firing scenarios, blended fuel properties were calculated using a weighted average based on mass fractions of each component. For example, in the 10 % biomass case, each fuel property (e.g., C, H, S, N, O, moisture, ash) in Table 1 was computed in Eq(1).

$$Blended\ property = (0.9\ \times Coal\ A\ value) + (0.1\ \times EFB\ value) \tag{1}$$

The same method was applied for the 3 % biomass blend. The resulting blended compositions were then assigned as user-defined solid fuels in ANSYS Fluent.

Table 1: Coal and EFB properties

Proximate Analysis, Dry Basis					
Solid Fuel	Volatile Matter (%)	Fixed Carbon (%)	Ash (%)	Total Moisture (%)	GCV (kcal/kg)
Coal A	25.91	52.96	13.77	7.36	6,232
EFB	82.4	10.09	7.51	7.3	4,039
Ultimate Analysis, Dry Ash Free Basis					
Solid Fuel	Carbon (%)	Hydrogen (%)	Oxygen (%)	Nitrogen (%)	Sulphur (%)
Coal A	83.9	4.67	8.14	2.05	0.76
EFB	42.8	6.2	50.44	0.47	0.09

3. Results and discussions

3.1 Furnace exit gas temperature.

FEGT is a key indicator of combustion performance, as it represents the intensity of heat released and affects how energy is transferred to the superheater sections. In this simulation, FEGT values were obtained by calculating the volume-weighted average temperature at the furnace outlet plane. The results clearly showed that FEGT decreased as the proportion of biomass in the fuel mix increased in Table 2.

Table 2: Simulated outlet emissions and comparison with plant references.

Case	FEGT (°C)
Case A	1,066.5
Case B	1,062.8
Case C	1,034.3

The decrease in flame temperature with higher EFB content is mainly due to its lower heating value and higher volatile content. EFB burns faster than coal but with less intensity, producing a more spread-out flame. Its ash can also absorb heat, which contributes to lower peak temperatures. Similar trends were reported by Jiang et al. (2020), who observed a drop in flame temperature from 1,526 °C to 1,476 °C when co-firing torrefied EFB in a 500 MWe boiler simulation. The reduction in furnace flame temperatures may decrease the tendency for slag formation on boiler walls, as lower temperatures inhibit ash melting; however, increased alkali and chlorine content in biomass can elevate fouling risk downstream in convective pass regions (Hariana et al., 2023).

Figure 3 shows the temperature distribution along the furnace midplane for each case. In the baseline (Figure 3a), the flame is compact and focused near the burner, with peak temperatures above 1,500 °C. With 3 % EFB (Figure 3b), the flame broadens slightly and shifts to lower intensity. At 10 % EFB (Figure 3c), the flame becomes more elongated and diffuse, with lower temperature gradients throughout the furnace. This reflects the thermal effect of biomass co-firing, even at low ratios. While lower flame temperatures may reduce thermal NOx, they could require burner or air staging adjustments to maintain heat transfer and performance.

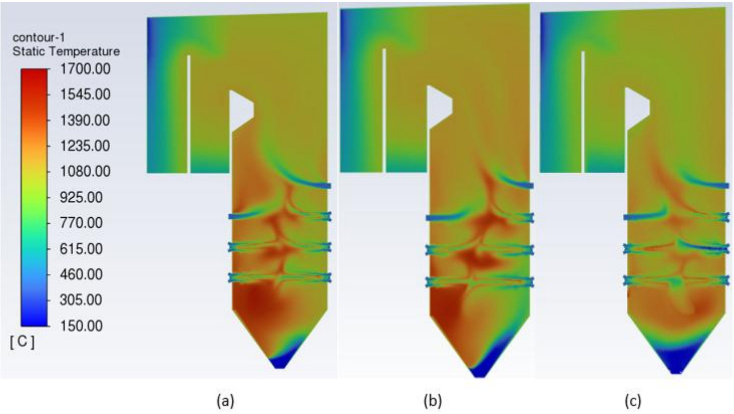


Figure 3: Static temperature contours at furnace midplane: a) Case A: 100 % Coal A, b) Case B: 3 % EFB co-firing, c) Case C: 10 % EFB co-firing.

3.2 Effect of biomass co-firing on pollutant emissions.

The impact of biomass co-firing on flue gas emissions was evaluated by analyzing CO, NOx, CO_2 at the boiler outlet. The emissions were compared across all three cases to assess combustion behavior, pollutant formation, and compatibility with operational benchmarks. The emissions results are summarized in Table 3, alongside reference plant values for NOx limit, CO limit, and CO_2 average.

Table 3: Simulated outlet emissions and comparison with plant references.

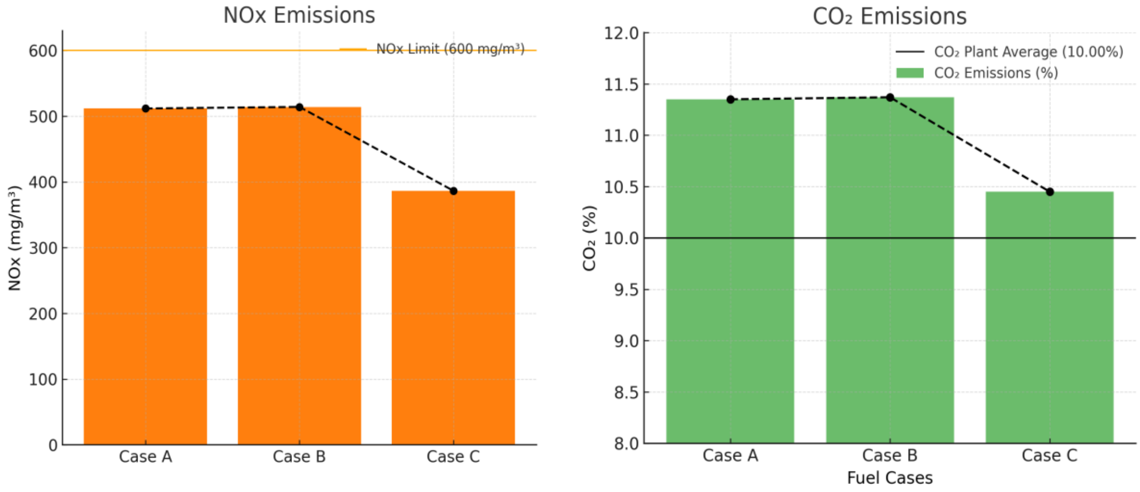
Case	NOx (mg/m³)	CO_2 (%)	CO (mg/m³)
Case A	511.8	11.35	0.036
Case B	514.2	11.37	0.052
Case C	386.6	10.45	0.699
Plant reference	<600	10.00 (avg.)	<200

All simulated emission values in Table 3 remained within acceptable limits except for CO emissions. NOx concentrations were well below the 600 mg/m³ threshold in all cases. The most notable reduction occurred in Case C, where NOx dropped to 386.6 mg/m³, a decrease of over 24 % from the baseline. This reduction corresponds with the lower flame temperature and decreased fuel-bound nitrogen associated with biomass co-firing, supporting the role of EFB as a practical option for NOx mitigation.

For CO_2, values in Cases A and B slightly exceeded the plant average of 10.00 %, recording 11.35 % and 11.37 %, respectively. In Case C, with 10 % EFB, CO_2 decreased to 10.45 %, approaching the plant average. The observed reduction aligns with the lower carbon content of EFB and its renewable nature. Although the CO_2 benchmark is not a strict regulatory limit, this trend supports biomass co-firing as a viable strategy to reduce fossil-derived carbon emissions in conventional coal-fired systems.

CO emissions were predicted to be very low in all cases, which is a known limitation of steady-state simulations using the non-premixed combustion model. This modelling approach assumes fast chemistry and ideal mixing, which tends to overpredict complete combustion and underpredict CO formation, particularly in localized fuel-rich or oxygen-deficient zones. Due to the underprediction and limited physical realism of the CO results, a CO emissions graph is not presented in Figure 4, and the values are discussed qualitatively for transparency.

Figure 4a compares NOx emissions across the three fuel cases using a dual-axis format, showing a clear reduction trend as the EFB ratio increases. The result aligns with findings by Sun et al. (2022), who reported systematic decreases in furnace peak temperature and NOx with biomass co-firing in a similar 300 MW boiler. Figure 4b shows steady declines in CO_2 concentrations, reflecting the lower carbon content of EFB compared to coal.



a)

b)

Figure 4: Effect of emission on (a) NOx at outlet for all cases and (b) CO_2 at outlet for all cases.

The results show that 10 % EFB co-firing leads to measurable reductions in both NOx and CO_2 emissions while remaining within acceptable regulatory limits.

4. Conclusions

This study demonstrates that low-ratio co-firing of EFB biomass in a 300 MW coal-fired boiler can reduce emissions without exceeding operational limits. At 10 % biomass, NOx emissions dropped by 24.5 % (from 511.8 to 386.6 mg/m³), and CO_2 declined from 11.35 % to 10.45 %, approaching the plant's average. FEGT remained within acceptable bounds, decreasing from 1,066.5 °C to 1,034.3 °C. Overall, the CFD approach used in this work provides a practical framework for evaluating co-firing strategies and supports efforts to achieve cleaner combustion in existing power plants. The results offer technical assurance for plant operators aiming to implement biomass co-firing without major infrastructure changes. However, this study is limited by its steady full-load operating condition and the use of simplified fuel properties. It also underpredicts CO emissions due to limitations in the combustion model and steady-state assumptions. Future work should consider transient operating conditions, variable load scenarios, more detailed combustion chemistry, and experimental validation to enhance model accuracy and practical relevance.

Nomenclature

CO_2 – Carbon Dioxide
CO – Carbon Monoxide
EFB – Empty Fruit Bunch
FEGT – Furnace exit gas temperature
PDF – Probability Density Function
DO – Discrete Ordinate
SST k-ω – Shear Stress Transport k-omega
SOx – Sulphur Oxide

Acknowledgments

The authors would like to thank Electricity Supplies Industry Trust Account (AAIBE), TNB Janamanjung (TNBJ), and Kapar Energy Ventures (KEV) for their support in this work, project no.: TNBR/AA 437/2024.

References

Bach Q.V., Khalil R.A., Tran K.Q., Skreiberg O., 2014, Torrefaction kinetics of norwegian biomass fuels. Chemical Engineering Transactions, 37, 49–54.

Black S., Szuhánszki J., Pranzitelli A., Ma L., Stanger P.J., Ingham D.B., Pourkashanian M., 2013, Effects of firing coal and biomass under oxy-fuel conditions in a power plant boiler using CFD modelling. Fuel, 113, 780–786.

Chen J., Li C., Ristovski Z., Milic A., Gu Y., Islam M. S., Wang S., Hao J., Zhang H., He C., Guo H., Fu H., Miljevic B., Morawska L., Thai P., Lam Y.F., Pereira G., Ding A., Huang X., Dumka U.C., 2017, A review of biomass burning: Emissions and impacts on air quality, health and climate in China. Science of The Total Environment, 579, 1000–1034.

Gazdallah M., Feldheim V., Claramunt K., Hirsch C., 2012, Finite volume method for radiative heat transfer in an unstructured flow solver for emitting, absorbing and scattering media. Journal of Physics: Conference Series, 369(1), 012020.

Hafiz M., Nelwan L.O., Yulianto M., 2018, CFD-based Analysis of Non-Premixed Combustion Model in Biomass Grate Furnaces. IOP Conference Series: Earth and Environmental Science, 147(1), 012029.

Hariana, Prabowo, Hilmawan E., Kuswa F.M., Darmawan A., Aziz M., 2023, A comprehensive evaluation of cofiring biomass with coal and slagging-fouling tendency in pulverized coal-fired boilers. Ain Shams Engineering Journal, 14, 102001.

Jiang Y., Park K.H., Jeon C.H., 2020, Feasibility Study of Co-Firing of Torrefied Empty Fruit Bunch and Coal through Boiler Simulation. Energies, 13, 3051.

Mularski J., Li J., 2023. A review on biomass ignition: Fundamental characteristics, measurements, and predictions. Fuel, 340, 127526.

Sun J., Zhao X., Xue D., 2022, Computational Fluid Dynamics Modeling of Biomass Co-Firing in a 300 MW Pulverized Coal Furnace. Thermal Science, 26, 4179 – 4191.

Wang J., Xiao Y., Fang Q., Ma L., Zhou F., Peng Z., Ma Q., Yin C., 2025, Biomass/coal co-firing in a 600 MW opposed wall-fired boiler: Impact of large non-spherical biomass particles on motion dynamics and boiler performance. Energy, 315, 134321.

Yao N.N., Chen Y.F., Wei L. M., Xu Q.Y., Pan W.G., 2025, Progress in CFD simulation for ammonia-fueled internal combustion engines and gas turbines. Journal of the Energy Institute, 119, 101951.