EXPERIMENTAL AND NUMERICAL INVESTIGATION OF CO-FIRING LIGNITE COAL WITH UPGRADED COAL AND BITUMINOUS COAL IN A DROP TUBE FURNACE

Viet Thieu Trinh[1,*], Pham Van Tan[1], Pham Anh Minh[1], Byoung-Hwa Lee[2], Kyeong-Ho Kim[2]

[1] School of Mechanical Engineering, Hanoi University of Science and Technology, No 1, Dai Co Viet street, Hai Ba Trung, Hanoi, Vietnam.

[2] Pusan Clean Energy Research Institute, Pusan National University, 2 Busandaehak-ro 63 beon-gil, Geumjeong-gu, Busan 46241, Republic of Korea.

*Corresponding Author: thieu.trinhviet@hust.edu.vn (V.T.T.).

This study investigates the co-firing of pulverized lignite coal with upgraded lignite coal and bituminous coal (Vitol) in a drop tube furnace with detailed computational fluid dynamics simulations. The research examines the impact of different coal blends on unburned carbon and nitrogen oxide (NOx) emissions under various co-firing ratios. Experimental results demonstrate that co-firing BRC with BHC leads to lower unburned carbon and NOx emissions compared to co-firing with Vitol. Specifically, increasing the proportion of BHC in the blend reduces unburned carbon but increases NOx, while increasing the proportion of Vitol elevates both unburned carbon and NOx. This trend is attributed to the higher nitrogen content of Vitol (4.43%) compared to BHC (1.13%). Computational fluid dynamics simulations provide detailed insights into the temperature distribution and NOx formation mechanisms under different blending conditions. The temperature distribution analysis reveals that co-firing broadens the combustion zones compared to single coal combustion due to variations in devolatilization and ignition times among the different coal types. The study underscores the importance of selecting compatible coal blends to optimize combustion efficiency and minimize emissions in coal-fired power plants

Key words*: Coal, Co-firing, Lignite, NOx, Fluent, Unburned carbon*

1. Introduction

The energy industry significantly harms the environment, and its heavy dependence on traditional energy sources jeopardizes the long-term viability of economic activities. Consequently, renewable energy sources (RES) are becoming increasingly important in the global energy sector and are seen as a viable alternative to fossil fuels [1]. However, despite the growing importance of renewable energy sources, fossil fuels still account for over 60% of global electricity generation in 2023. In fact, according to the IEA's Coal 2023 Analysis and forecast to 2026, global coal consumption reached a record high in 2022, increasing by 4% from the previous year to 8.42 billion tonnes. This growth was driven mainly by China and India, where demand increased by 4.6% and 9%, respectively [2] . Therefore, to remain economically viable, existing coal-fired power plants must shift from continuous base-load operation to flexible operation that can quickly adapt to fluctuating demand, especially due to the intermittent nature of RES [3].

Lignite, a lower-quality coal, is widely used for electricity generation in numerous countries. Lignite-fired power plants require more fuel and larger facilities to produce the same amount of electricity as bituminous coal power plants due to lignite's higher moisture content, greater tendency to cause ash buildup, and lower energy content [4,5]. Despite these drawbacks, extensive research on lignite utilization for power generation is being conducted both in power plants and laboratories. Blending is one of the most viable methods for utilizing low-rank coal such as lignite [6–9]. Lee *et al.* (2011) [10] and Trinh *et al.* [11] investigated the influence of coal blending methods on UBC and nitrogen oxide (NOx) emissions in a drop-tube furnace (DTF). The researchers examined different blending methods, including layered and premixed arrangements, to determine their effects on combustion efficiency and pollutant formation. The study revealed that the layered arrangement, where different coal types were placed in distinct layers, resulted in lower UBC and NOx emissions compared to the premixed arrangement. This finding highlights the importance of considering coal blending methods in optimizing combustion processes and minimizing emissions. The use of a DTF in this study allowed for precise control of experimental conditions and accurate measurement of combustion characteristics, demonstrating the effectiveness of DTF as a research tool for investigating coal combustion. Coal blending is becoming increasingly popular in thermal power plants due to its potential to improve economic efficiency by allowing for a wider range of fuel options. However, it's important to note that interactions between the different coal components in the blend can occur, and these interactions may have both positive and negative effects [12,13]. Therefore, it's crucial to accurately assess the compatibility of different coal types in blends to ensure efficient combustion. Moreover, the increasing global energy demand and subsequent rise in atmospheric pollutants have put immense pressure on the thermal power sector using pulverized coal to reduce emissions. As a result, research on technical methods for pollutant emission reduction remains a vital and ongoing area of study. Upgrading lignite through drying, carbonization, briquetting, gasification, and liquefaction can transform this fuel into a cleaner and more efficient fuel source [4,14]. These processes not only reduce greenhouse gas emissions and pollutants but also optimize the utilization of existing reserves, contributing to energy security and economic development.

To address these challenges, this study aims to investigate and compare the combustion characteristics of raw lignite coal, upgraded coal, and bituminous coal. In the experimental phase, a drop tube furnace will be utilized to simulate the high heating rate conditions typically encountered in thermal power plants. The study will analyze the amount of UBC and NOx emissions produced during the combustion process. This analysis will be conducted for individual coal types (raw lignite, upgraded coal, and bituminous coal) as well as for mixtures of these coal types at various ratios. By examining the UBC and NOx emissions under different scenarios, the study seeks to identify the coal type or mixture that exhibits the most favorable combustion characteristics in terms of efficiency and environmental impact. In addition to the experimental work, in the numerical phase, computational models will be developed to simulate the combustion process and validate the experimental findings. These models will incorporate relevant parameters such as coal properties, operating conditions, and furnace geometry. By comparing the numerical results with the experimental data, the study aims to refine the models and enhance their predictive capabilities. Ultimately, this study provides valuable insights with practical applications for optimizing coal blending strategies in power plants to minimize emissions and improve combustion efficiency. The findings on UBC and NOx emissions for different coal blends can inform the selection of coal types and blending ratios to achieve these goals. For instance, power plants can use the results to identify coal blends that minimize UBC while keeping NOx emissions within acceptable limits. The study also highlights the importance of considering the properties of different coal types, such as volatile matter and nitrogen content, when designing blending strategies. Additionally, the insights into the impact of co-firing on combustion zones and temperature distribution can be used to optimize burner design and operation. By understanding the influence of co-firing on these parameters, engineers can better control the combustion process to reduce emissions and improve efficiency.

2. Experimental section

2.1. Materials

Table 1. Proximate and ultimate analysis results

Sample	Proximate analysis (ARB), wt%)				Ultimate analysis (DAF), wt%)					HHV (ARB, kJ/kg)
	Moist.	V.M.	Ash	F.C.	C	H	N	O	S	
BRC	32.6	23.4	13.5	30.5	77.48	4.60	0.87	16.18	0.86	14,758
BHC	0.33	34.4	16.66	48.61	74.65	4.77	1.13	18.60	0.85	23,492
Vitol	7.43	26.41	17.14	49.02	82.59	5.28	4.43	7.26	0.45	26,727

[1)] ARB : As received basis; [2)] DAF : Dry ash - free.
BRC: Lignite coal; BHC:Upgraded BRC coal.

Table 1 presents the proximate and ultimate analysis results of three coal samples: lignite coal (BRC), upgraded lignite coal (BHC), and bituminous coal (Vitol). Coal analyses were conducted according to the following standards: ISO 17246:2010 and ISO 12902:2014. The analyses were performed at the Pusan Clean Energy Research Institute, an accredited laboratory according to ISO/IEC 17025:2017. The BRC, plentiful in Ulaanbaatar, Mongolia, fuels local power plants, generating both electricity and heat. Due to its inherent high moisture content, BRC requires upgrading to satisfy power plant specifications. A process developed by KIER addresses this issue, producing BHC with reduced moisture. This study compares the combustion properties of BRC, the BHC, and a reference bituminous coal (Vitol coal, widely used in South Korean thermal power plants) employing both experimental and computational methodologies.

Analysis of BRC, BHC, and Vitol coals reveals key differences in their fuel properties. Upgrading lignite (BRC to BHC) significantly reduces moisture and increases volatile matter, improving combustion. However, BHC exhibits slightly higher ash and lower heating value (HHV) than bituminous Vitol coal. Vitol has the highest HHV (26,727 kJ/kg), followed by BHC (23,492 kJ/kg) and BRC (14,758 kJ/kg). BRC's high moisture (32.6 wt%) classifies it as low-rank. BHC's high volatile matter (34.4 wt%) suggests good ignition. Vitol has the highest carbon content (82.59 wt%). Nitrogen content, influencing NOx emissions, is highest in BRC (1.13 wt%). These findings inform coal suitability for various applications. In addition to this data, sieve analysis revealed that BRC, BHC particles, and Vitol coal particles were smaller than 75 micrometers. The coal samples were pulverized to a mean particle size of 75 μm, with 90% of the particles passing through a 200-mesh sieve. This information is crucial for understanding and optimizing the combustion process, as particle size significantly influences factors like ignition, flame propagation, and burnout. This comprehensive analysis provides a basis for comparing the fuel properties of these coals and understanding their potential performance in combustion applications.

2.2. Experimental apparatus

The DTF, a widely used apparatus in combustion research, was employed to investigate the combustion characteristics of BRC, BHC, and Vitol coals [10,11]. The experimental procedure is depicted in this diagram as Fig 1. This setup investigates coal combustion by precisely controlling the reacting gases and monitoring the products. Nitrogen (N2) as the primary gas (1) and a nitrogen-oxygen (N2 + O2) mixture as the secondary gas (2) are carefully introduced, their flow rates managed by mass flow controllers (MFCs). A screw feeder (3) delivers coal particles into the coal reactor (5) where they ignite and burn in a controlled manner, facilitated by the oxygen in the secondary gas. The resulting mixture of exhaust gases and solid particles is separated using a cyclone (6), and the gas stream is further cleaned by a filter (7). A pump (8) then directs the cleaned gas to a gas analyzer (9) to measure its composition. UBC is removed from the reactor bottom. This specific DTF, illustrated in Fig. 1, is a vertical, electrically heated furnace consisting of three distinct zones: an injection zone for fuel introduction, a reaction zone where combustion occurs, and a collection zone for capturing ash and gas samples. Pulverized coal samples were fed into the DTF at a controlled rate of 0.2 g/min, with combustion taking place under a stoichiometric ratio of 1.2 (excess air). The residence time of pulverized coal particles in the DTF was estimated to be approximately 1.2 seconds, based on the gas flow rate and the furnace dimensions. The DTF's design allows for rapid heating rates (10^4 - 10^5 K/s), mimicking conditions in industrial boilers, enabling the study of devolatilization, ignition, and char oxidation. UBC in the collected ash was determined gravimetrically using loss-on-ignition (LOI) at 950^{o}C, while NOx emissions were measured using a gas analyzer (e.g., chemiluminescence detector) downstream of the DTF. To ensure accuracy, the DTF temperature was calibrated using thermocouples, and gas flow rates were regulated by mass flow controllers. Replicate experiments were conducted to assess reproducibility, and error analysis, incorporating uncertainties in fuel feed rate, temperature, and gas analysis, was performed, typically resulting in uncertainties of ±5% for UBC and ±10% for NOx. To minimize experimental errors, each experimental trial was repeated three times. The results presented are the average of these repetitions. Ash samples were carefully collected from the collection zone after each run, ensuring representative sampling by taking multiple aliquots from different locations within the ash deposit. These samples were then dried and homogenized before UBC analysis. This detailed methodology aims to provide a comprehensive understanding of the combustion behaviour of the investigated coal samples. The experiments were carried out at the Pusan Clean Energy Research Institute in September 2023.

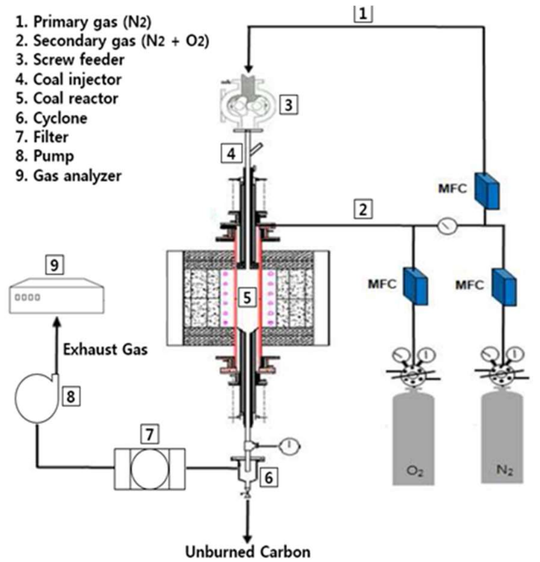


Fig. 1. Schematic diagram of DTF test equipment

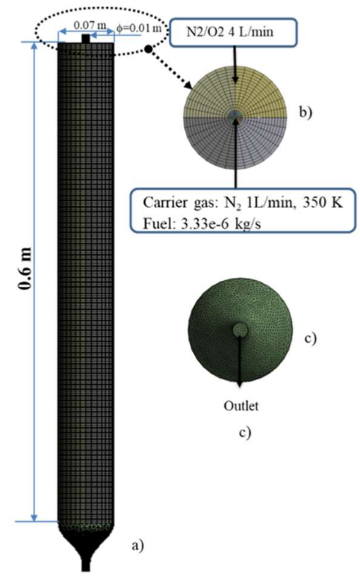


Fig. 2. Geometry and mesh of DTF: (a) Front view (b) Top view (c) Bottom view

3. Mathematical model and computer code

ANSYS FLUENT 20R1, a commercial Computational Fluid Dynamics (CFD) software [15,16], was used to numerically analyze and predict the co-firing process of coal in a DTF. The gas and solid particle phases were simulated using Eulerian and Lagrangian approaches, respectively. The aerodynamics of the turbulent flow within the DTF was computed using a steady-state Reynolds Averaged Navier-Stokes (RANS) approach with the Realizable k-epsilon turbulence model. The stochastic particle trajectory model was employed to analyze the flow of fuel particles within the DTF. Due to the high accuracy of the temperature distribution and the small optical length inside the DTF, the Discrete Ordinate model was used to calculate the radiative heat transfer equation. The Weighted-Sum-of-Gray-Gas Model (WSGGM) was used to determine the absorption coefficient of the gas for radiative heat transfer calculations. This model provides a balanced approach between an overly simplistic gray gas model and a more complex model that accounts for specific absorption bands. Chemical reactions, including the combustion of volatiles from coal and biomass fuels, were calculated using the finite rate/eddy dissipation model, which controls the reaction rate considering the combustion rate and mixing rate. A two-step reaction mechanism was applied to calculate the gas phase reactions, representing the reaction between oxygen and fuel and the reaction between carbon monoxide and oxygen to calculate the combustion of volatiles released during combustion. The devolatilization model of coal was calculated using the first-order model, and the single-rate model was used for the fuel. The char burnout of coal and biomass fuel was calculated using the Kinetics/Diffusion limited model, which determines the combustion rate considering the chemical reaction rate and diffusion. The kinetics values for devolatilization and char burnout reactions were directly used from the second-year experimental data.

This numerical analysis uses a NOx post-processing model to analyze nitrogen oxide emission characteristics for each condition. Prompt NOx is not included in the prediction due to its small generation amount, and only Fuel NOx and Thermal NOx are considered. Fuel NOx is formed from nitrogen combined in solid fuel. Some of the Fuel NOx is generally released as HCN and NH3 along with volatile matter and is finally oxidized to NO or reduced to N2. Thermal NOx is formed by the oxidation of atmospheric nitrogen in a relatively high-temperature zone in a fuel-lean environment and has a high-temperature dependency in the boiler furnace. In the case of coal, it is estimated that 90% of the nitrogen contained in volatile matter is converted to HCN, and the rest produces NH3 [17,18]. The geometry for the analysis was the internal alumina tube flow field of the DTF, and 3D analysis was performed to conduct a computational analysis of the device, mirroring the experimental setup. To model the shape for computational analysis, 3D modeling and grid generation were performed using ANSYS DesignModeler. This approach aligns with the methodology used in similar studies, where CFD simulations are employed to investigate the flow behavior and combustion processes within DTF [11]. Fig. 2 illustrates the three-dimensional (3D) shape and grid of the DTF used in the computational analysis. The computational model has a diameter of 0.07 meters and a total length of 0.6 meters. The model is divided into two distinct areas: the primary area (PA) and the secondary area (SA). The PA corresponds to the injection part where fuel and transport gas are introduced, while the SA represents the injection part for the reaction gas, which facilitates the combustion of the fuel.

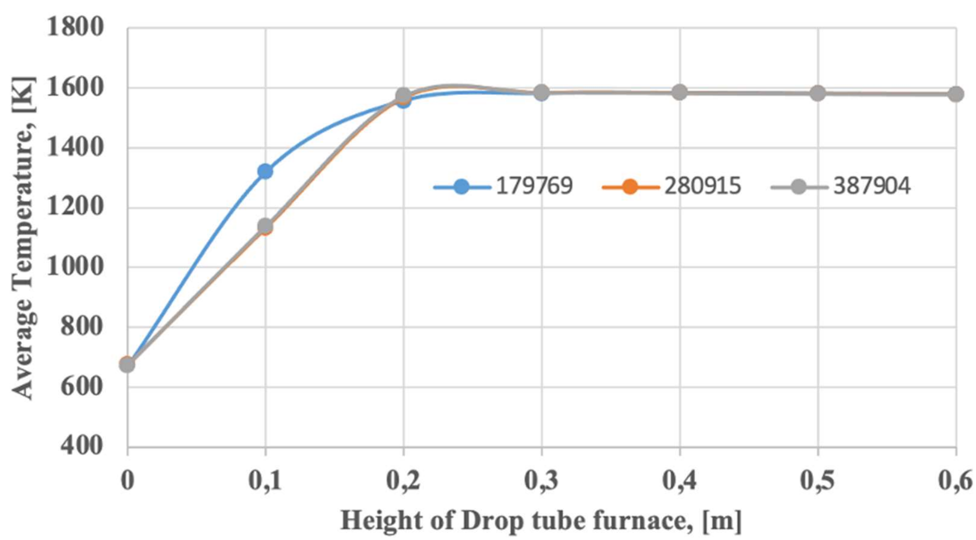


Fig. 3. Average Temperature Variation with DTF Height.

As illustrated in Fig. 3., three distinct mesh resolutions were evaluated, comprising 179,769, 280,915, and 387,904 elements. Notably, the temperature profile generated by the coarsest mesh (179,769 elements) exhibited a marked deviation from the other two, particularly within the region characterized by a sharp temperature gradient. Conversely, the profiles obtained using 280,915 and 387,904 elements demonstrated a high degree of congruence, with minimal discernible differences observed. This convergence indicates that the numerical solution achieves mesh independence beyond a refinement of 280,915 elements. Consequently, the mesh comprising 280,915 elements was deemed sufficiently refined to accurately resolve the thermal characteristics within the Drop Tube Furnace (DTF), balancing computational efficiency with solution accuracy. This grid structure is well-suited for analyzing the axial flow of gases and particles, which are injected from the top and exit at the bottom of the furnace. To enhance numerical stability, the portion of the DTF model beyond the PA injection part is designed to extend uniformly in a radial shape. This approach is consistent with established practices in CFD modeling of similar combustion systems.

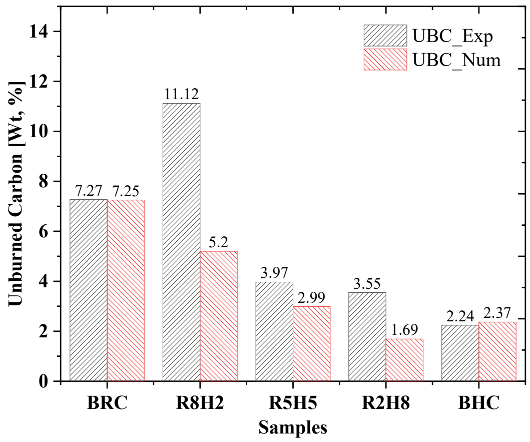
Table 2. DTF test conditions

Parameters	Units	Values
Coal mass flow	kg/s	3.33e-6
Wall temperature	K	1573
Mass flow rate of primary air	kg/s	2.033e-5
Temperature of fuels	K	350
Volume flow rate of secondary air	kg/s	8.133e-5
Coal size	µm	75
Excess oxygen	-	1.2

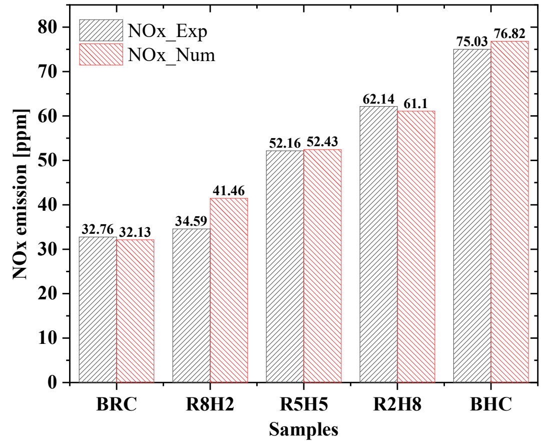
The fuel utilized in the computational analysis of combustion to examine emission characteristics, based on coal type and co-firing ratio in the DTF, is identical to the fuel used in the DTF experiment. This computational analysis is conducted under conditions consistent with the experiment. The injection conditions of the coal fuel are detailed in Tab. 2. This approach of using consistent fuel properties and operating conditions between experimental and computational analyses is common in combustion research to ensure the validity and applicability of the simulation results. The following parameters were measured during the DTF experiments: wall temperature, gas flow rates (primary and secondary air), flue gas composition (O2, CO2, NOx) and UBC in fly ash.

4. Results and discussion

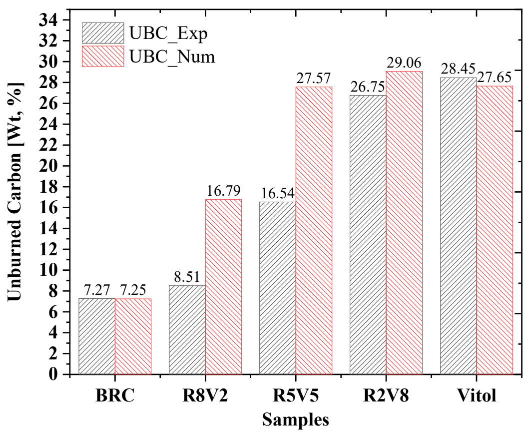
The combustion behavior of fuel blends is influenced by the mass fractions of the constituent fuels and their inherent properties. In this study, the mass fractions of fuel samples were systematically varied (0%, 20%, 50%, 80%, and 100%) to investigate the impact of co-firing substantial proportions of BHC and Vitol coal with BRC. The resulting effects on combustion characteristics and ash behavior are illustrated in Fig. 4. Figure. 4 presents the experimental and simulation results of UBC and NOx emissions from the combustion of single coal types (BRC, BHC, and Vitol) and their blends at various mass fractions. The co-firing of BRC with BHC resulted in lower UBC and NOx emissions compared to co-firing with Vitol coal. This suggests that BHC is more compatible with BRC in terms of combustion efficiency and emissions control. The results indicate that increasing the mass fraction of BHC in the blend decreases UBC but increases NOx emissions. Conversely, increasing the mass fraction of Vitol leads to an increase in both UBC and NOx emissions. This observation aligns with the understanding that Vitol coal is harder to burn than BHC, as evidenced by the higher UBC of single Vitol (28.45%) compared to BHC (2.37%). Under standard state conditions (0°C and 1 atm pressure) at the DTF outlet, the concentration of NO (ppm), the volume fraction of O2, and the carbon burnout rate decreased with an increase in BHC/Vitol ratio.



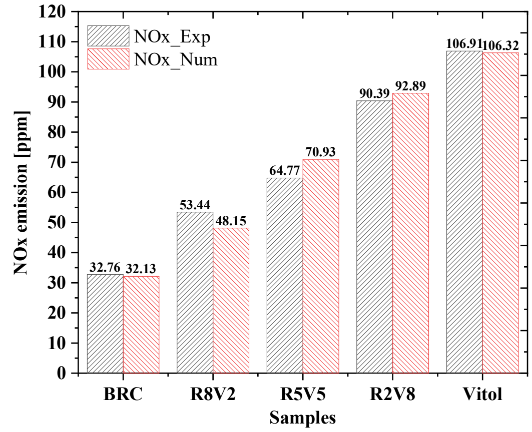
a) UBC of mixture BRC and BHC



b) NOx emission of mixture BRC and BHC



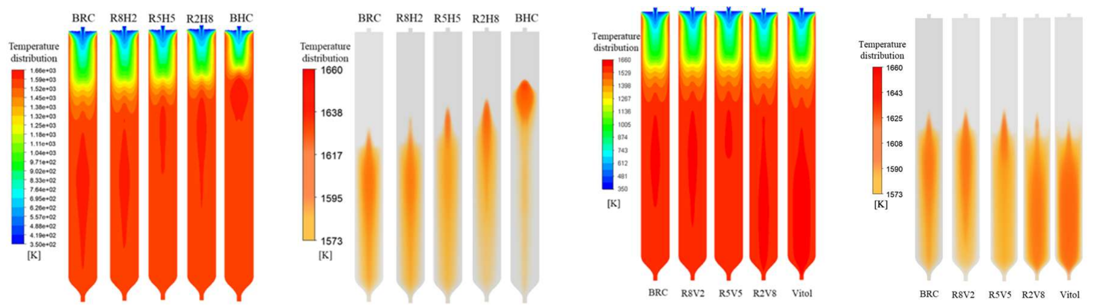
c) UBC of mixture BRC and Vitol



d) NOx emission of mixture BRC and BHC

Fig. 4. Comparison of experimental and simulation results in term of UBC and NOx (ppmvd, 6%O2) according to BRC fuel and co-firing ratio; (a)(b) with BHC, (c)(d) with Vitol

The increase in NOx emissions with increasing BHC and Vitol mass fractions is consistent with the nitrogen content of each coal type. This phenomenon can be attributed to fuel NOx formation, which occurs when nitrogen in the fuel reacts with oxygen in the combustion air. The thermal NOx formation, another mechanism contributing to NOx emissions, is influenced by temperature. Higher temperatures promote the conversion of nitrogen-containing species (HCN, NH3) formed from coal volatiles into NO rather than N2 [10,16,19]. Figure. 5 presents the results of the computational temperature distribution within the DTF for various coal types and co-firing ratios. After the fuel and gas enter the DTF, the fuel is rapidly dried and heated due to the high-temperature environment. Ignition occurs at a certain distance from the inlet, initiated by the release of volatiles from the pulverized coal. The volatiles combust rapidly, releasing a significant amount of heat and creating a high-temperature zone. The temperature range along the furnace height varies from approximately 350 K to 1660 K. In the case of single coal combustion, a single high-temperature peak is observed, corresponding to the combustion zone of the specific coal type. However, in co-firing scenarios, the combustion zones are extended, and the extent of this extension depends on the mass fraction of BHC or Vitol coal in the blend. This phenomenon is attributed to the different devolatilization and ignition times of each coal type. The staggered release and combustion of volatiles from different coals promote the overall devolatilization and ignition process, leading to broader combustion zones.



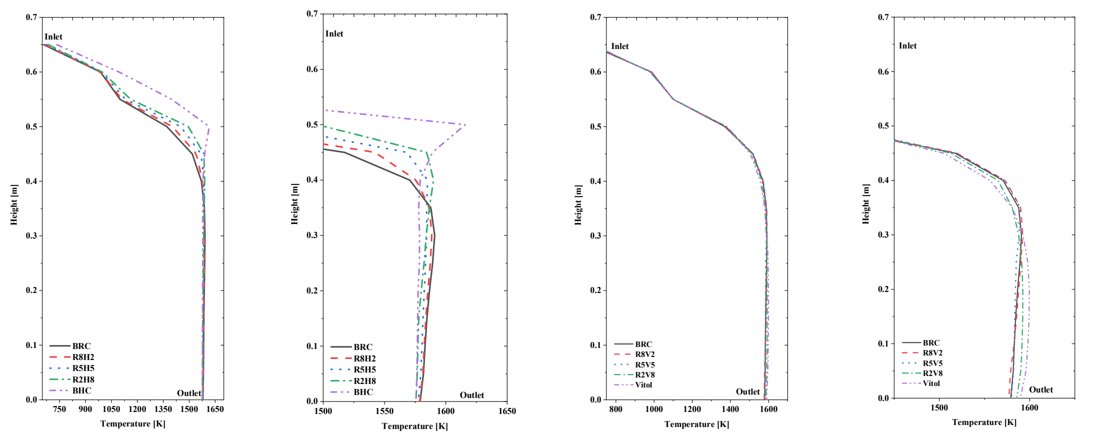
a) Temperature distribution of blending BRC and BHC

b) High temperature zone of blending BRC and BHC

c) Temperature distribution of blending BRC and Vitol

d) High temperature zone of blending BRC and Vitol

Fig. 5. Temperature distribution in vertical cross section



a) Mass-weighted average in horizontal cross section of blending BRC and BHC

b) Mass-weighted average in horizontal cross section of blending BRC and BHC at high temperature zone

c) Mass-weighted average in horizontal cross section of blending BRC and Vitol

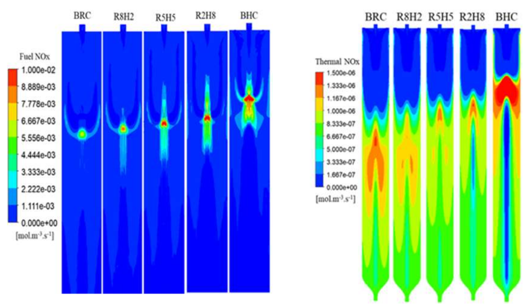
d) Mass-weighted average in horizontal cross section of blending BRC and Vitol at high temperature zone

Fig. 6. Average temperature distribution in vertical cross section

The vertical distribution of average temperature, illustrated in Fig. 6, demonstrates a correlation between the extent of the high-temperature zone and the percentage of BRC. Decreasing the proportion of BRC shifts the combustion zone further from the inlet, indicating that high moisture content delays combustion. The burning zone of BHC (0.15 m from the air inlet) is closer than that of H8R2 (0.2 m), H5R5 (0.2 m), H2R8 (0.35 m), and BRC (0.35 m), suggesting delayed combustion. The highest temperature of BHC (1616 K) is higher than that of BRC (1590 K), implying that the thermal NOx of BHC will be higher than that of BRC. Outlet temperatures decrease with increasing BHC percentage, an effect caused by delayed combustion. The high-temperature zone also depends on the percentage of Vitol. The combustion zone shifts further from the inlet, indicating that the ignition and combustion characteristics of Vitol coal make it harder to burn. The high-temperature zone (1573-1660 K) is larger for Vitol than BRC, suggesting that the thermal NOx of Vitol will be higher than that of BRC. To quantitatively analyze the variation characteristics of NO concentration along the height of the DTF, several horizontal sections were taken. The area-weighted average NO concentration under standard state of the flue gas on each horizontal section was calculated. This approach aligns with previous studies where the impact of fuel blending ratios and combustion conditions on NOx emissions has been investigated.

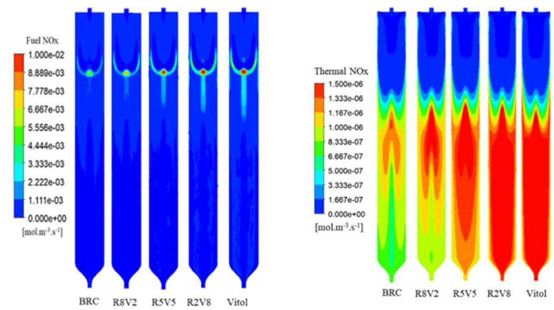
Figures 7 and 8 illustrate the distribution of fuel and thermal NOx formation rates for mixtures of BRC with BHC or Vitol coal. Fuel NOx was calculated based on the nitrogen content of the coal and the conversion ratio mentioned earlier. Thermal NOx was calculated using the Zeldovich mechanism, which considers the reaction of nitrogen and oxygen at high temperatures. Figures 7a and 8a show that Fuel NOx formation is consistent with the combustible content of the fuel. Generally, increasing the percentage of BHC or Vitol coal in the blend increases NOx emissions. However, NOx emissions are higher when blended with Vitol than with BHC at the same percentage. This is because Vitol coal has a higher nitrogen content (4.43%) compared to BHC (1.13%). Similar to the work by Moon *et al.* [12], this study found that the co-firing of lignite and bituminous coals can lead to lower NOx emissions compared to using bituminous coal alone. For co-firing with bituminous coal and lignite, the blends with 10% lignite showed a minimum value for NOx concentration and similar temperature distribution as the bituminous coal case. For other lignite blending ratios, however, NOx concentrations increased with increasing blending ratio of lignite. In other words, there is a critical blending ratio of lignite that results in a positive NOx reduction without the loss of combustion efficiency. However, this study also includes BHC, which adds a unique aspect to the research. Similar to Lu *et al.* [20], this study found that decreasing the load in the furnace can reduce NO emissions. In the context of 75% THA (Turbine Heat Acceptance), there is a sharp decline in the amount of pulverized coal and air volume, which causes the temperature in the boiler to drop significantly. This makes a significant difference to the level of NO concentration in the boiler. Both studies utilize numerical simulations to analyze combustion characteristics and emissions, but Lu *et al.* focus on a tangentially fired pulverized coal boiler subjected to peak-load regulation, while this study utilizes the DTF. As the ratio of BHC/Vitol increases, the combustible components (volatile matter and char) also increase, leading to an increase in Fuel NOx. The presence of moisture in BRC delays Fuel NOx formation, meaning the peak Fuel NOx rate occurs further from the burner inlet compared to the blends.

In BRC and BHC blends, the position of thermal NOx formation tends to move closer to the burner as the BHC ratio increases. The maximum thermal NOx formation is observed for pure BHC combustion, indicating that BHC contributes more to thermal NOx than BRC or other blends. Vitol coal, being harder to burn, has a combustion zone further from the inlet, resulting in thermal NOx emissions also being further from the inlet. This is evident in Fig. 7a, where Fuel NOx increases with increasing Vitol coal ratio due to the increase in combustible components. These findings align with previous studies on NOx formation mechanisms in coal combustion. Fuel NOx is primarily formed from the nitrogen present in the fuel, while thermal NOx is formed from the reaction of nitrogen and oxygen in the combustion air at high temperatures. The higher nitrogen content of Vitol coal and the delayed combustion of BRC due to moisture contribute to the observed trends in NOx emissions.



a) Fuel NOx b) Thermal NOx

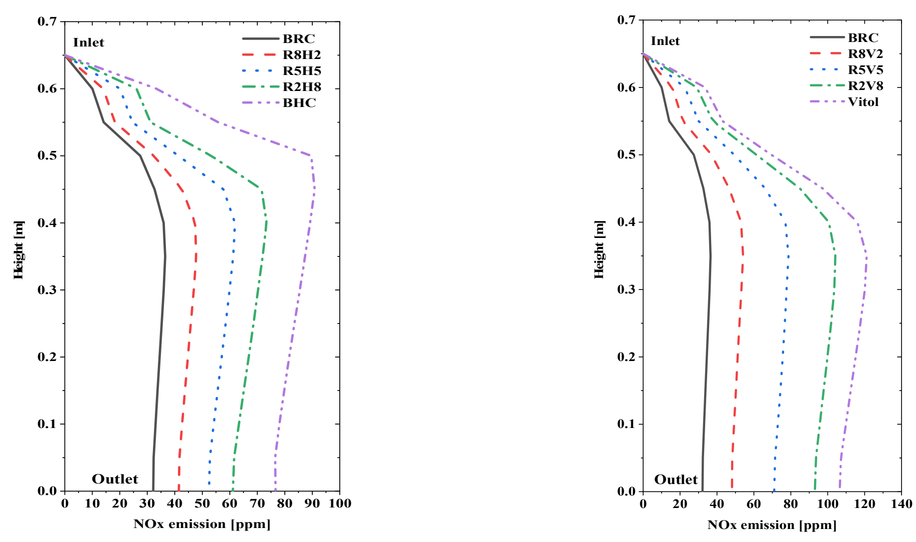
Fig. 7. Distributions of NOx formation rates of mixture of BRC and BHC



a) Fuel NOx b) Thermal NOx

Fig. 8. Distributions of NOx formation rates of mixture of BRC and Vitol

Figure 9 illustrates the NOx emission trends along the DTF height for various coal blends. Higher proportions of BHC or Vitol in the blends generally lead to increased NOx emissions, particularly in the lower part of the furnace. This is attributed to the higher volatile matter content in BHC and the higher nitrogen content in Vitol.



a) Blending of BRC and BHC b) Blending of BRC and Vitol

Fig. 9. NOx emission with DTF height

5. Conclusions

This research explored the combustion characteristics of different coal blends using a drop tube furnace and CFD modeling, providing valuable insights for optimizing coal combustion processes in thermal power plants. The study found that co-firing lignite coal with BHC resulted in lower UBC and NOx emissions compared to co-firing with bituminous coal. Increasing the proportion of upgraded lignite in the blend led to a decrease in UBC but an increase in NOx emissions. Conversely, increasing the proportion of bituminous coal increased both UBC and NOx emissions, suggesting that bituminous coal is more difficult to combust and contributes more to NOx formation. The CFD simulations revealed that co-firing extended the combustion zones compared to single coal combustion, which was attributed to variations in devolatilization and ignition times among the different coal types. Analysis of NOx formation showed that fuel NOx increased with higher proportions of upgraded lignite or bituminous coal, while thermal NOx was more pronounced in upgraded lignite combustion. These findings have significant implications for improving efficiency, reducing emissions, and enhancing environmental sustainability in coal-fired power plants. Power plant operators can utilize the results of this study to optimize coal blending strategies by selecting appropriate coal types and blending ratios to minimize UBC and NOx emissions. The insights into the impact of co-firing on combustion zones and temperature distribution can be used to optimize burner design and operation, further improving combustion efficiency and reducing emissions. The results also provide valuable data for validating and refining CFD models, enabling more accurate predictions of combustion behavior and emissions for various coal blends and operating conditions. This improved predictive capability can aid in the design and optimization of future power plants and combustion systems. By implementing the findings of this study, the coal-fired power generation sector can move towards a cleaner and more sustainable future.

Acknowledgements

This research is funded by Hanoi University of Science and Technology (HUST) under project number T2023-TĐ-015.

Funding information: funding provided by Hanoi University of Science and Technology (HUST).

References

[1] Galimova, T., *et al.,* Global demand analysis for carbon dioxide as raw material from key industrial sources and direct air capture to produce renewable electricity-based fuels and chemicals, *J. Clean. Prod.,* 373 (2022), 133920

[2] International Energy Agency, Coal 2023 - Analysis and forecast to 2026, 2023.

[3] Khalili, S., *et al.,* Role and trends of flexibility options in 100% renewable energy system analyses towards the Power-to-X Economy, *Renewable and Sustainable Energy Reviews, 212* (2025), 115383.

[4] Liu, M., *et al.,* Energy and water conservation at lignite-fired power plants using drying and water recovery technologies, *Energy Convers. Manag., 105* (2015), pp. 118–26.

[5] Xu, G., *et al.,* An integrated lignite pre-drying system using steam bleeds and exhaust flue gas in a 600 MW power plant, *Appl. Therm. Eng., 107* (2016), pp. 1145–57.

[6] Drosatos, P., *et al.,* Numerical Comparative Investigation of a Flexible Lignite-Fired Boiler Using Pre-Dried Lignite or Biomass as Supporting Fuel. Renew. *Energy,* 145 (2020), pp. 1831–48.

[7] Atimtay, A.T., *et al.,* Co-firing of pine chips with Turkish lignites in 750 kWth circulating fluidized bed combustion system. *Bioresour. Technol.,* 224 (2017), pp. 601–10.

[8] Bian, C., *et al.,* Numerical optimization of combustion and NOX emission in a retrofitted 600MWe tangentially-fired boiler using lignite. *Appl. Therm. Eng.,* 226 (2023), 120228.

[9] Drosatos, P., *et al.,* Comparative investigation of a co-firing scheme in a lignite-fired boiler at very low thermal-load operation using either pre-dried lignite or biomass as supporting fuel. *Fuel Processing Technology,* 180 (2018), pp. 140–54.

[10] Lee, B.H., *et al.,* Impact of Pulverize Coal Particle Sizes on Combustibility an NOx Emission in Different Blening Methos. *Energy and Fuels,* 33 (2019), pp. 12814–21.

[11] Trinh, V.T., *et al.,* Prediction of ash deposition in a biomass boiler using thermomechanical analysis. *Journal of Industrial and Engineering Chemistry*, 131 (2024), pp. 481–9.

[12] Moon, C., *et al.,* NOx emissions and burnout characteristics of bituminous coal, lignite, and their blends in a pulverized coal-fired furnace. *Exp. Therm. Fluid Sci.,* 62 (2015), pp. 99–108.

[13] Milićević, A., *et al.,* Numerical study of co-firing lignite and agricultural biomass in utility boiler under variable operation conditions. *Int. J. Heat Mass Transf.,* 181 (2021), 121728.

[14] Chantasiriwan, S., Improvement of conventional design of lignite-fired thermal power plant by integrating steam-air preheater and flue gas dryer. *Energy Conversion and Management: X*, 15 (2022), 100272.

[15] Karampinis, E., *et al.,* Numerical investigation Greek lignite/cardoon co-firing in a tangentially fired furnace. *Appl. Energy*, 97 (2012), pp. 514–24.

[16] Trinh, V.T., *et al.,* Numerical Optimization on Char Conversion and NOx Emission under Various Operating Conditions in a Retrofit Biomass Boiler. *ACS Omega*, 8 (2023), pp. 18530–42.

[17] Liu, M., *et al.,* Numerical investigation of ammonia/coal co-combustion in a low NOx swirl burner. *Energy*, 282 (2023), 128358.

[18] Wang, C., *et al.,* Investigation on Co-Combustion Characteristics and NOx Emissions of Coal and Municipal Sludge in a Tangentially Fired Boiler. *Fuel*, 340 (2023), 127608.

[19] Wei, D., *et al.,* Numerical simulation of ammonia combustion with sludge and coal in a utility boiler: Influence of ammonia distribution. *Journal of the Energy Institute*, 111 (2023), 101409.

[20] Lu, H., *et al.,* Numerical simulation of combustion characteristics in a 660 MW tangentially fired pulverized coal boiler subjected to peak-load regulation. *Case Studies in Thermal Engineering*, 49 (2023), 103168.

Submitted: 06.12.2024.
Revised: 05.03.2025.
Accepted: 13.03.2025.