



Numerical Study of Ammonia and Coal Co-Firing Using Combustion Model in Drop Tube Furnace

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ABSTRACT:

This study presents a numerical investigation of coal and ammonia (NH_3) co-firing using Computational Fluid Dynamics (CFD) within a Drop Tube Furnace (DTF). The objective is to evaluate the influence of ammonia blending on combustion characteristics and pollutant formation. Using CFD in ANSYS Fluent, simulations were conducted at various ammonia blending ratios (25%, 50%, and 75% by calorific value) to analyze temperature distribution and the formation of CO_2 , CO, and NO_x . The results indicate that increasing ammonia concentration significantly reduces peak combustion temperatures due to its lower heating value and the formation of water vapor, which absorbs a portion of the released thermal energy. CO_2 emissions decreased substantially with higher ammonia content, as ammonia contains no carbon. However, co-firing with higher ammonia ratios led to elevated levels of CO and NO_x emissions, primarily due to incomplete combustion and the nitrogen content inherent in NH_3 . In particular, NO_x emissions spiked at the 75% ammonia level, highlighting the need for effective mitigation strategies such as air staging, burner optimization, and post-combustion treatments. Overall, while ammonia shows promise as a carbon-free fuel alternative, careful combustion system design is crucial to ensure high thermal efficiency and regulatory compliance.

Keywords: ammonia, coal, co-firing, CFD simulation, combustion, emissions, NO_x , CO_2 reduction

INTRODUCTION

Over the past two years, global coal-fired power generation has experienced a significant surge, contributing to over 36% of total electricity production worldwide. Consequently, carbon dioxide (CO_2) emissions from coal-fired plants have risen drastically, making them one of the world's largest sources of CO_2 and posing serious threats to the climate and ecosystems. To limit global temperature rise to $1.5^\circ C$, phasing out coal for power generation by 2030–2040 is essential (Asif et al., 2022; Mills, 2018; Vögele et al., 2018; Yang et al., 2019; Zhang et al., 2022).

Many countries have already taken steps or announced plans to eliminate the use of fossil fuels such as coal. In Indonesia, however, the main energy sources remain coal, oil, and gas, which collectively account for about 88.7% of energy production. Among these, coal is the largest contributor to emissions. To address this issue, carbon neutrality efforts have been initiated, primarily by improving energy conversion efficiency. One strategy involves the use of absorption technologies to capture CO_2 from exhaust gases (*flue gas*). Additionally, adopting low-carbon fuels that are environmentally friendly is considered a promising approach. The most viable solution appears to be switching to fuels with low carbon intensity, as they directly reduce emissions.

Ammonia (NH_3) has been identified as a feasible alternative fuel for electricity generation, particularly in developed countries, due to its carbon-free emissions. When burned completely, it produces nitrogen and water as combustion products. NH_3 also possesses a higher volumetric energy density than other low-carbon fuels such as hydrogen (H_2). Moreover, NH_3 transitions from gas to liquid more easily than H_2 . Mixing ammonia with other fuels, such as coal, can help lower

combustion temperatures and reduce emissions. With growing concern about climate change, ammonia shows increasing potential as a future fuel source.

Numerous experimental investigations and computational modeling studies have been conducted to explore the potential benefits of using ammonia as a fuel. In Japan, the technology company IHI tested a 10 MW pulverized coal boiler by performing co-firing experiments with a 20% ammonia mix ratio based on calorific value (Ishii et al., 2022). The results showed that when the mixture ratio was optimized, the combustion process remained stable and comparable to that of 100% coal combustion. Similarly, Yamamoto et al. (2018) successfully demonstrated ammonia and coal co-firing under controlled laboratory-scale conditions using a specialized burner.

Another study conducted by Brouwer et al. (1996) focused on simulating pure ammonia combustion in a simple horizontal furnace. The objective of the study was to analyze combustion behavior and emission characteristics. The results indicated that at a 10% ammonia concentration, NO_x emissions were at their lowest. However, increasing the ammonia concentration led to higher NO emissions and exhaust gas temperatures due to ammonia's *de-NO_x* effect, which initially reduces but subsequently increases NO formation in the exhaust.

Lyu et al. (2023) conducted a 3D computational fluid dynamics simulation on a 600 MW coal-fired boiler to analyze ammonia co-firing. The simulation results indicated that ammonia combustion inside the furnace was generally feasible. However, increasing the ammonia blend ratio resulted in reduced combustion efficiency and a rise in NO_x emissions.

Jin et al. (2023) also carried out an experimental study on a 1050 MW boiler with ammonia injection into the secondary air stream. They observed that ammonia co-firing led to higher flame temperatures and NO concentrations within the combustion chamber. Another study by Kim et al. (2023) investigated ammonia and coal co-firing in a laboratory-scale pulverized coal (PC) boiler model and reported reduced flame stability and combustion efficiency due to the thermal and chemical characteristics of ammonia.

Given these findings, the present study aims to evaluate the impact of ammonia co-firing on coal combustion performance, particularly focusing on thermal efficiency and pollutant emissions. This study investigates ammonia co-firing at three mixing ratios—25%, 50%, and 75% based on calorific value—using a Drop Tube Furnace (DTF). Additionally, the research examines the resulting changes in furnace temperature and flue gas emissions, including CO, CO₂, and NO_x.

METHOD

Drop Tube Furnace (DTF)

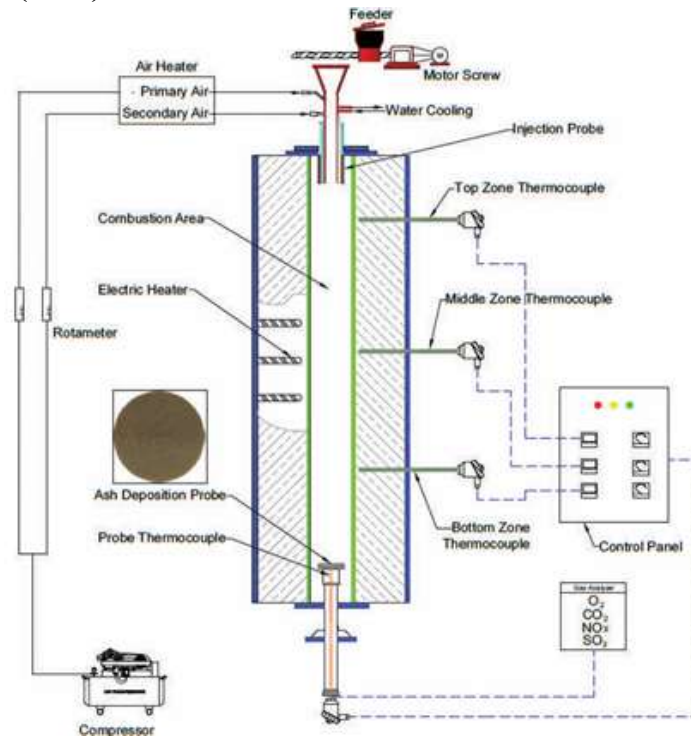


Fig. 1 Skema DTF [5]



Fig. 2 3D Drop Tube Furnace and meshing

Figure 1 presents the schematic of a laboratory-scale Drop Tube Furnace (DTF) system designed for studying coal particle combustion behavior. The furnace has a thermal capacity of 1

kWth and is constructed in a vertical orientation, with an overall height of 1.5 meters and an internal diameter of approximately 0.07 meters (Fig 2). The system functions as a controlled combustion reactor, simulating high-temperature, short-residence-time combustion conditions similar to those found in industrial burners.

The furnace is electrically heated using coil-type heaters, which are divided into three separate heating zones. This zoning ensures uniform temperature distribution (isothermal conditions) along the vertical length of the furnace, which is essential for maintaining stable combustion and reproducible experimental results.

Coal particles are fed into the system using a motor-driven screw feeder. To maintain a consistent and uninterrupted feed of fuel particles, the feeder is equipped with a vibrating mechanism that helps prevent clogging and ensures steady flow. The coal particles are injected into the furnace through the center of a cooling probe injector. This injector is actively cooled using water to prevent premature ignition of the fuel caused by the high ambient temperature near the injection point.

Combustion occurs inside the cylindrical chamber of the furnace, with a downward flow of hot gases—replicating a suspension-fired combustion environment. Combustion air is supplied in two streams: primary air at a flow rate of 3 liters per minute and secondary air at 4 liters per minute. Both air supplies are preheated in an oven to a temperature of 180°C to facilitate efficient ignition and combustion of the fuel.

The coal feed rate ranges from 0.045 to 0.060 kilograms per hour and is introduced into the furnace together with the preheated primary air through the upper cooling probe. The combustion gases produced in the process are extracted via a lower cooling probe and directed to a gas analyzer for detailed analysis. The analyzer measures the concentrations of critical combustion gases, including oxygen (O₂), carbon dioxide (CO₂), carbon monoxide (CO), nitrogen monoxide (NO), and sulfur dioxide (SO₂). This data is crucial for evaluating combustion performance, emission characteristics, and the efficiency of the system (Brouwer et al., 1996).

Simulation CFD

In this study, numerical simulations were conducted using the commercial CFD software ANSYS Design Modeler and Fluent version 2022 R1 (ANSYS Inc.), which is widely used for solving fluid flow problems, especially during combustion processes involving solid fuels. The modeling focuses on a three-dimensional (3D) representation of a Drop Tube Furnace (DTF) reactor. The numerical simulations solve a set of governing equations including mass, momentum, enthalpy, and temperature.

The analysis also incorporates turbulence modeling, heat transfer via radiation, and the combustion reactions occurring between solid fuel particles (coal) and the gas phase (air). Particle motion in the gas flow field is modeled using the Eulerian-Lagrangian approach, which allows accurate tracking of particle trajectories. Additionally, a devolatilization model based on global

Arrhenius kinetics is applied to estimate the rate at which volatile gases are released from the fuel particles due to increasing temperature.

Meshing of the DTF reactor domain uses an tetrahedral mesh comprising 6,227,847 nodes and 1,547,308 elements to ensure high numerical accuracy and stability.

1. Species Model: The **Non-Premixed Combustion model** was applied to describe the equilibrium behavior of chemical species including **C, H, O, N, S**, and fuel properties such as **volatile matter, fixed carbon, and moisture content**. The model predicts thermal NO_x and SO₂ emissions from combustion reactions.

2. Boundary Conditions:

- a. **Fuel mass flow rate:** 1.38e-05 kg/s (at 335 K)
- b. **Air mass flow rate:** 1.6e-04 kg/s (at 335 K)
- c. **Furnace wall condition:** Isothermal at 1300 K, wall roughness 0.5, internal emissivity 1
- d. **Probe wall:** Isothermal at 335K.

To simulate the combustion process of Low-Rank Coal (LRC) and ammonia (NH₃) under different co-firing ratios, **ANSYS Fluent 2022 R1 CFD** software was utilized. The simulation was applied to drop tube furnace, as well as to a coal-fired under steady-state conditions. The **standard k-ε turbulence model** was employed in this study. This semi-empirical model is widely used due to its practical applicability, cost efficiency, and reliable accuracy.

The CFD simulation is governed by three fundamental equations:

1. **Continuity equation** (mass conservation)

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

2. **Momentum conservation equation** (Newton's second law)

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

3. **Energy conservation equation** [34]

$$\frac{\partial}{\partial t} (\rho E) + \nabla \cdot [\vec{v} (\rho E + p)] = -\vec{v} \cdot \left(\sum_j h_j J_j + S_h \right) \quad (3)$$

The co-firing process involving ammonia and coal includes two distinct combustion mechanisms: coal combustion and ammonia combustion. The coal combustion model comprises two major stages—namely, the devolatilization phase (in which volatile compounds are released) and the gas-phase combustion. The kinetic parameters used in this process refer to the work by Du et al. (2017).

The chemical reactions involved in coal combustion are described through Equations (4) to (7), covering the production of carbon monoxide (CO), carbon dioxide (CO₂), water vapor (H₂O), and hydrogen (H₂). In contrast, ammonia combustion consists of two key stages: ammonia pyrolysis (the breakdown of NH₃ into N₂ and H₂) and its subsequent combustion reactions with oxygen and NO, as outlined in Equations (8) to (10). The characteristics of ammonia combustion were derived from well-established references used for kinetic rate benchmarks (Monnery et al., 2001; Jin et al., 2023).

Table 1. The characteristics of ammonia combustion

Coal Combustion	Volatile + O₂ → H₂O + N₂	(4)
	CO + 0.5O ₂ → CO ₂	(5)
	CO + H ₂ O → CO ₂ + H ₂	(6)
	H ₂ + 0.5O ₂ → H ₂ O	(7)
Ammonia Pyrolysis	NH ₃ → 0.5N ₂ + 1.5H ₂	(8)
Ammonia	NH ₃ + O ₂ → NO + H ₂ O + 0.5H ₂	(9)
Combustion	NH ₃ + NO → N ₂ + 0.5H ₂	(10)

In this study, the coal specifications were based on a certified Certificate of Analysis (COA), which includes critical parameters such as chemical composition, calorific value, moisture content, ash content, and volatile matter. These data are essential for accurately assessing combustion behavior and thermal efficiency during the co-firing process. Additionally, the calorific value of ammonia was also considered to evaluate the energy contribution of this alternative fuel. Detailed information on both fuels is presented in Table 2 and table 3, which outlines the key parameters used as the foundation for numerical modeling and thermal performance analysis of the combustion system.

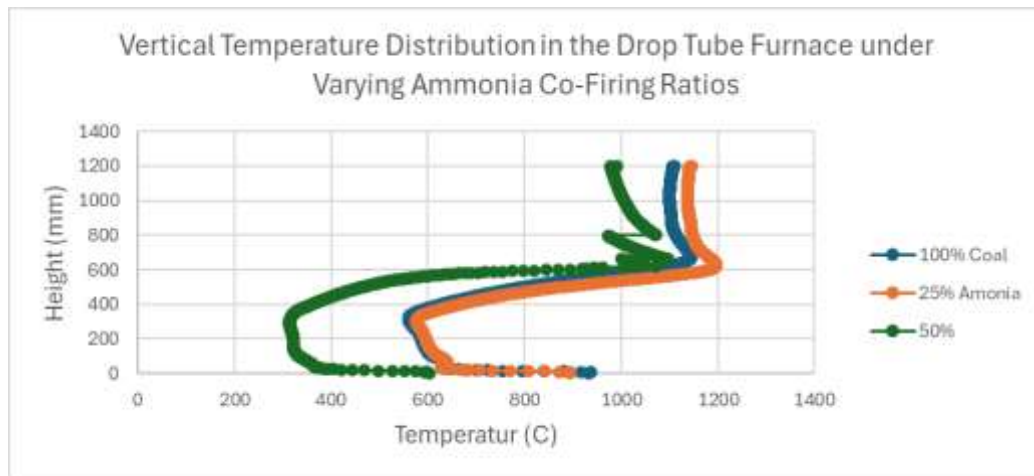
Table 2. COA Coal

PROXIMATE ANALYSIS				
DATA	ADB	UNIT		
Total Moisture (TM)	17.66	%		
Ash Content (A)	5.02	%		
Volatile Matter (VM)	41.47	%		
Fixed Carbon (FC)	35.85	%		
Total Content	100	%		
ULTIMATE ANALYSIS				
DATA	ADB	DB	DAF	UNIT
Carbon (C)	54.43	66.1	70.4	%
Hydrogen (H)	4.87	5.91	6.3	%
Nitrogen (N)	0.78	0.95	1.01	%
Sulfur (S)	0.26	0.32	0.34	%
Oxygen (O)	16.98	20.62	21.95	%
Ash	5.02	6.1	0	%
Moisture	17.66	0	0	%
Total Content	100.00	100	100	%
HHV (AR)	4079.00			Kcal/kg

Table 3. NH₃ Specification

Fuel	NH ₃
Boiling temperature at 1 atm (°C)	-33.4
High heating value (MJ/kg)	22.5
Maximum laminar burning velocity (m/s)	0.07
Minimum auto ignition temperature (°C)	650
Flame speed (cm/s)	7-9

RESULTS AND DISCUSSION

**Fig. 3 Distribution Temperature**

The addition of ammonia as a fuel in the cofiring process with coal can lead to a decrease in combustion temperature inside the furnace, as shown in figure 3. Based on the data and visualizations obtained, both from the temperature versus height curve and the simulated temperature distribution, there is a clear trend of decreasing temperature with increasing ammonia ratio in the fuel mixture. Under 100% coal conditions, the maximum temperature in the furnace can reach around 1230 °C, whereas with up to 75% ammonia cofiring, the temperature drops significantly to approximately 1140 °C. This indicates that the greater the proportion of ammonia in the fuel mixture, the lower the heat energy produced during combustion.

The primary factor contributing to this temperature decrease is the physical and chemical properties of ammonia itself. Ammonia has a lower heating value compared to coal, meaning that for the same mass of fuel, the heat energy released from ammonia combustion is less than that from coal. Additionally, ammonia contains a high amount of hydrogen, which when burned, produces a large quantity of water vapor (H₂O). Water vapor has a high heat capacity and tends to absorb a significant portion of the heat from the combustion process. This accumulation of water vapor results in lower peak temperatures in the main combustion zone and affects the overall heat distribution inside the furnace.

Furthermore, the increased concentration of water vapor due to ammonia combustion also impacts the post-combustion zone (afterburner zone) and the overfire air (OFA) zone. This water vapor reduces the efficiency of heat transfer by radiation within the furnace, as combustion gases containing high levels of water vapor absorb more heat but transfer less energy to the furnace walls and heating pipes. This condition may lead to a reduction in overall boiler performance because the flue gas exiting the furnace carries less heat energy, resulting in less effective water heating in the heat exchanger area.

The temperature distribution from the simulation in Figure 3.1 also shows a gradual reduction in high-temperature zones (indicated in red) from the 100% coal condition to the 50% ammonia mixture. This reinforces that using a high proportion of ammonia in cofiring should be carefully considered to maintain combustion efficiency and the thermal performance of the boiler. While ammonia can be a more environmentally friendly alternative fuel, especially in the context of reducing carbon emissions, its impact on temperature reduction and combustion system performance needs to be further analyzed and optimized to avoid negatively affecting overall plant efficiency.

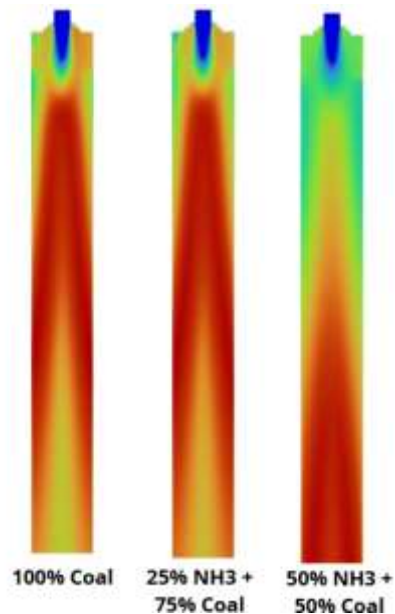


Fig. 4 Counter Temperature

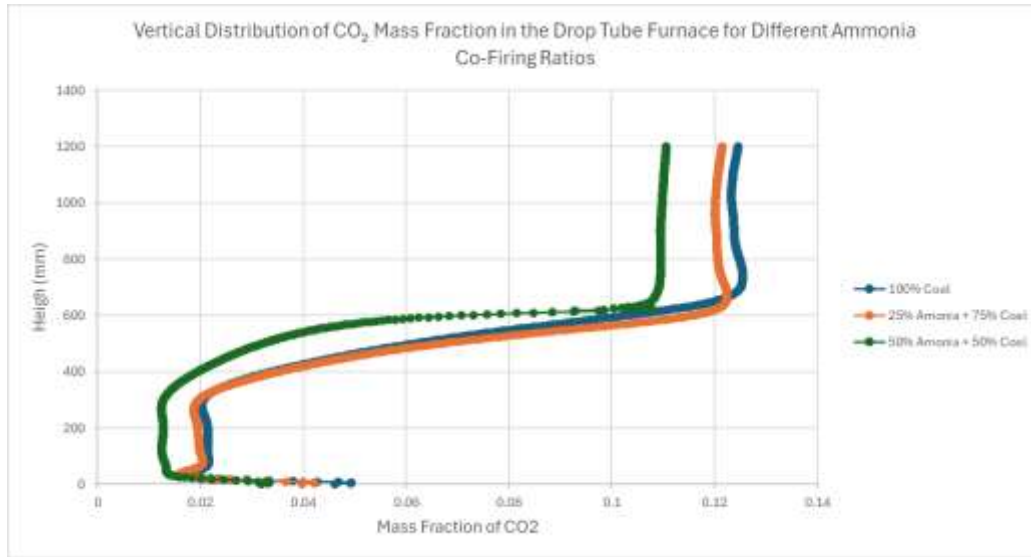


Fig. 5 Graphic Mass Fraction CO₂ vs High

Figure the relationship between the mass fraction of CO₂ and the combustion chamber height for various fuel mixture scenarios involving coal and ammonia (co-firing). It clearly shows that as the proportion of ammonia in the fuel mixture increases, the CO₂ mass fraction produced during combustion significantly decreases. In the case of 100% coal combustion, the CO₂ mass fraction reaches its highest values, indicating that coal, being a carbon-rich fossil fuel, produces the most CO₂ emissions.

When ammonia is introduced into the fuel mixture—such as in the 25% ammonia and 75% coal scenario—the CO₂ levels begin to drop noticeably across almost all heights of the furnace. This trend continues more prominently in the 50% and 75% ammonia blends, where the overall CO₂ mass fractions are significantly lower. This reduction is primarily because ammonia (NH₃) contains no carbon, and thus does not produce CO₂ when burned. As a result, the higher the ammonia content in the co-firing mixture, the less CO₂ is emitted during combustion.

The distribution pattern also indicates that at higher elevations within the furnace (above 600 mm), the CO₂ mass fraction remains lower for higher ammonia mixtures compared to 100% coal. This confirms that replacing a portion of coal with ammonia is an effective strategy for reducing greenhouse gas emissions from coal-fired power plants. However, it's important to note that while CO₂ emissions are reduced, the impact on combustion performance and thermal efficiency must be carefully evaluated. This is because fuel mixture variations also affect the flame temperature and combustion behavior throughout the furnace.

CONCLUSION

Co-firing coal with ammonia reduces combustion temperature as the ammonia ratio increases, primarily due to its lower heating value and the high water vapor content generated during combustion. Carbon dioxide (CO₂) emissions decrease significantly at higher ammonia ratios, since ammonia contains no carbon. In contrast, carbon monoxide (CO) and nitrogen oxide

(NO_x) emissions increase—particularly at 50% and 75% ammonia ratios—because of incomplete combustion and the high nitrogen content in NH_3 . While ammonia shows promise as a low-carbon alternative fuel, high-ratio usage presents technical challenges, especially in terms of flame stability and NO_x emission control. To optimize coal–ammonia co-firing, advanced strategies such as staged combustion, burner design adaptation, and post-combustion emission reduction technologies like Selective Catalytic Reduction (SCR) are required.

For future research, it is essential to move beyond fundamental combustion analysis and focus on developing and optimizing mitigation strategies for the identified drawbacks. Subsequent studies should numerically and experimentally investigate advanced combustion techniques such as air staging, rich-lean burners, or flameless oxidation specifically designed for ammonia–coal blends, in order to suppress NO_x formation without compromising combustion efficiency. Furthermore, research should explore the integration and effectiveness of post-combustion capture technologies, such as SCR, tailored to the unique *flue gas* composition resulting from high-ratio co-firing. Finally, to ensure practical applicability, future work should scale up the simulations to model full-scale industrial boilers under various load conditions, providing a comprehensive techno-economic analysis for the implementation of ammonia co-firing in real-world power plants.

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