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Performance and Emission Analysis of Ammonia-Diesel Blend in a Compression Ignition Engine

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Abstract

This study examines the performance and emissions characteristics of a compression ignition engine operating with an ammonia-diesel blend as fuel. Ammonia, a carbon-free fuel, is combined with diesel to address environmental concerns associated with traditional diesel engines while maintaining efficiency. A single-cylinder, 4-stroke engine was modified for dual-fuel operation, with ammonia contributing 20% of the energy input. Experiments under varying loads analyzed brake power, torque, fuel consumption, and emissions (CO_2, CO, HC, and NO_x). Results reveal that ammonia reduces CO_2 emissions and lowers diesel fuel consumption due to its energy contribution, while slightly improving brake power and torque at higher loads. However, the blend increases NO_x and HC emissions, emphasizing the need for optimized combustion strategies. These findings highlight the potential of ammonia-diesel blends as a transitional low-carbon fuel for sustainable energy solutions.

Keywords— *ammonia combustion, diesel, compression ignition engine, dual-fuel, performance, emissions*

Introduction

The global reliance on fossil fuels for power generation and transportation has led to significant concerns regarding environmental sustainability and climate change [1]. Traditional diesel engines, widely used in heavy-duty applications due to their high efficiency and durability, contribute to greenhouse gas emissions, notably carbon dioxide (CO_2), and harmful pollutants like nitrogen oxides (NO_x) and particulate matter (PM) [2], [3]. These emissions have not only accelerated global warming but have also affected air quality, prompting worldwide regulatory efforts to reduce pollutants from internal combustion engines (ICEs) [4]. As a result, there is an urgent demand for alternative, cleaner fuels that can sustain engine efficiency while meeting stricter emission standards.

Among alternative fuels, hydrogen, natural gas, and biodiesel have each offered paths toward reducing emissions, but each comes with its own challenges, such as storage, energy density, and compatibility with existing engine infrastructure. More recently, ammonia (NH_3) has emerged as a promising candidate for low-carbon fuel in combustion engines due to its energy density, carbon-free molecular structure, and well-established infrastructure for production and transport in industries like agriculture [5], [6], [7]. Ammonia's zero-carbon content means that, when used as a fuel, it produces no CO_2 emissions directly, offering a potentially viable way to decarbonize conventional engines. Despite its advantages, ammonia presents technical challenges for combustion engines, especially in compression ignition (CI) engines, which are traditionally designed for diesel fuel. Ammonia has a high ignition temperature and low flame speed, which makes it difficult to ignite and sustain stable combustion

independently. However, blending ammonia with diesel provides a promising solution, combining ammonia's environmental benefits with diesel's favorable combustion characteristics. In a dual-fuel approach, diesel fuel serves as the primary ignition source, leveraging its high cetane number to initiate and sustain combustion, while ammonia contributes as a secondary fuel to lower CO_2 emissions and improve sustainability.

Scholars have conducted numerous studies on ammoniadiesel. Wang et al. [8] investigated the effects of diesel fuel injection timing and 0-90% ammonia energy ratio (AER) on combustion and emissions on a 4-cylinder turbocharged engine. Their experiments demonstrated that a low to medium to high percentage of ammonia helps reduce N_2O emissions, and optimizing injection timing helps reduce unburned ammonia. Zaher et al. [9] examined the effects of ammonia injection into the intake manifold on greenhouse gas emissions and soot formation in a dual-fuel (DF) diesel engine. The study evaluated ammonia energy shares of 20% and 40%, with tests conducted under constant engine speed and load conditions.

Zheng et al. [10] conducted experimental research to examine the combustion dynamics and emissions of a dual-fuel engine operating with high ammonia energy ratios. Findings revealed that while high ammonia content significantly lowered carbonbased emissions, it introduced combustion stability challenges and elevated NOx levels. The study emphasized the importance of optimizing ammonia-diesel ratios and ignition strategies to improve engine efficiency while minimizing environmental impacts. Arivalagan et al. [11] investigated the potential of ammonia-diesel fuel blends as a low-carbon alternative in compression ignition engines. The study evaluated the impact of these blends on engine performance, efficiency, and emissions using experimental methods and machine learning techniques. Results highlighted that increasing ammonia content reduced CO_2 emissions but posed challenges, such as higher NOx emissions and reduced combustion efficiency.

Xu et al. [12] conducted research by exploring the potential of using ammonia as an emission-free fuel for ship propulsion in a dual-fuel engine, utilizing the reactivity-controlled compression ignition (RCCI) concept. Yousefi et al. [13] conducted experimental and numerical investigations of a dual-fuel compression

ignition engine powered by ammonia and diesel fuel. The research showed that increasing the energy fraction of ammonia reduced the thermal efficiency of the dual-fuel engine compared to the combustion mode using only diesel fuel. Also, that increasing the ammonia energy share from 0 to 40% reduced nitrogen oxides (NOx) and increased carbon dioxide (CO_2) emissions. Dupuy et al. conducted research on the efficiency and emissions of a single-cylinder dual-fuel compression ignition engine with 2% energy share of diesel and 98% energy share of ammonia. Experiments focused on the influence of the NH_3-air fuel mixture composition on CO_2, CO, NH_3, NOx and N_2O emissions, stable engine operation was achieved for a small ammonia share (IMEP changes did not exceed 5%). The study revealed that reducing the amount of diesel in the pilot injection may not necessarily be the best strategy for minimizing the carbon footprint and CO emissions.

Due to the increasing popularity of ammonia as an engine fuel, especially in stationary application, more and more research is being conducted and the knowledge about ammonia combustion in piston engines is continuously growing particularly in a compression ignition engine operating in dual-fuel mode. Despite this, further research to provide accurate data, while improving efficiency and optimizing future ammonia-powered engines, is required. To this end, the performance and exhaust emissions characteristics of the diesel fuel and the ammonia-diesel blend are therefore studied, with ammonia contributing 20% of the total energy supplied to the engine. By examining the potential for ammonia-diesel dual-fuel engines, this research aims to support the transition toward cleaner engine technology and contribute to the development of sustainable energy solutions for transportation, stationary, and industrial applications. This study explores the combustion characteristics of ammonia-diesel blends in CI engines, analyzing the effects of ammonia concentration on engine performance and emission behaviours at various loads.

EXPERIMENTAL PROCEDURE

A. Experimental Setup

For this research, a single-cylinder, 4-stroke compression ignition (CI) engine was used to carry out the experimental work. The detailed specifications of the engine are given in Table 1. The CI engine was modified to operate on ammonia-diesel

dual-fuel mode. In this study, diesel was injected directly into the combustion chamber, while gaseous ammonia was introduced through a secondary port injection system. The schematic diagram and photographs of the experimental setup are shown in Fig. 1(a) and 1(b) respectively. All experimental studies were conducted at the Universiti Teknologi PETRONAS (UTP).

Table 1: Engine specification parameters of the CI engine

Engine Specifications	Value
Engine type	Single cyl., air-cooled
Cylinder bore (mm)	86
Maximum stroke (mm)	75
Cylinder displacement (cc)	434
Maximum engine speed (rpm)	3600
Maximum power output (kW)	6.8
Number of strokes	4
Compression ratio	20 ± 0.3

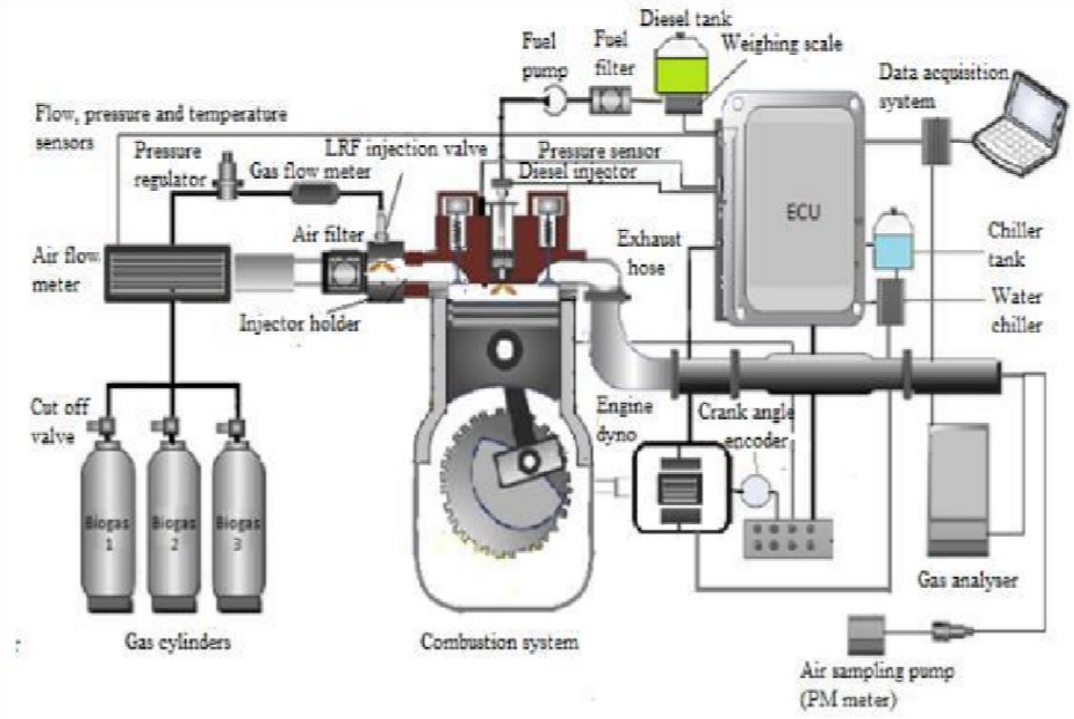


Figure 1: Schematic diagram of the test rig



Figure 2: The experimental setup

The operation of the engine for the experimental work was managed and controlled by a PC-based data acquisition and control system developed in the LabVIEW environment. Data was recorded after the engine operation became stable. The in-cylinder pressure was measured using a water cooled Kistler piezoelectric pressure transducer. Also connected to the data acquisition system was the crank angle encoder, which was used to establish the location of the crank angle position. The power from the engine was measured using a direct current (DC) dynamometer. The Kane AUTOplus Exhaust Gas Analyzer was used in this study to measure the concentration of carbon monoxide (CO), carbon dioxide (CO_2), nitrogen oxides (NOx), hydrocarbon (HC) and oxygen (O_2) for each gas. A Coriolis flow meter measured the ammonia mass flow rate. The fuel gas supply line system includes ammonia fuel cylinder, diesel tank, pressure regulators, a fuel mass flow meter, and pressure gauges. The fuels used in carrying out the experiment research were pure diesel and diesel blended with of ammonia concentration at 20% by energy.

The tested diesel fuel properties are shown in Table 2. The reaction equation presented in equations 3.1 and 3.2 were used to describe the combustion processes for the diesel and air; and for the diesel-ammonia blend and air, respectively.

Table 2: Fuel properties

Property	**Value**
Fuel	Diesel
Density (kg/m^3)	826
Calorific value (kJ/kg)	43500
Kinematic viscosity (mm^2/s)	2.55
Cetane Number	42.5
Flash point (^{0}C)	49.2

$$C_{13}H_{28} + 20\,O_2 \implies 13CO_2 + 14H_2O \quad (3.1)$$

$$C_{13}H_{28} + 4NH_3 + 26\,O_2 \Longrightarrow 13CO_2 + 20H_20 + 4NO_2 \quad (3.2)$$

Methodology

All tests and measurements were carried out on a CI engine with the throttle adjusted to the required engine speed of 1500 rpm and a fixed injection timing of 20 deg before top dead center (bTDC). The experiments were conducted using diesel fuel as the reference, with ammonia comprising 20% of the energy fraction, supplied at a flow rate of 1.5kg/h, under varying load conditions of 0%, 25%, 50%, 75%, and 100%. At these conditions, the effects on engine performance, combustion and emissions were examined. Prior to data acquisition, the engine was operated to reach a steady state. For each fuel sample, the experiment was repeated 3 times under the same conditions. Since the investigation involves measuring and analyzing brake torque, brake power, fuel consumption and recording emissions, the uncertainties of the instruments used for testing are shown in Table 3.

Table 3: *Accuracy of the measurements*

Parameters	Value
Fuel flow rate	Diesel
Engine speed (rpm)	$\pm$ 1 to 3

Emission (ppm)	± 5

RESULTS AND DISCUSSION

A. Performance Characteristics

Brake Power and Torque

Figures 3 and 4 show that the brake power and the brake torque increase with load. They are directly proportional since the engine speed is kept constant. At the engine increased up to 50%, 0.2 kW of brake power was recorded when diesel fuel is used. However, at higher engine load of 75% and 100%, 0.6 and 0.8 kW of brake power were noted, respectively. Upon addition of ammonia to diesel fuel, brake power improved across all engine loads. At 75% and 100% loads, the engine realized brake powers of 0.8 and 1.0kW, respectively.

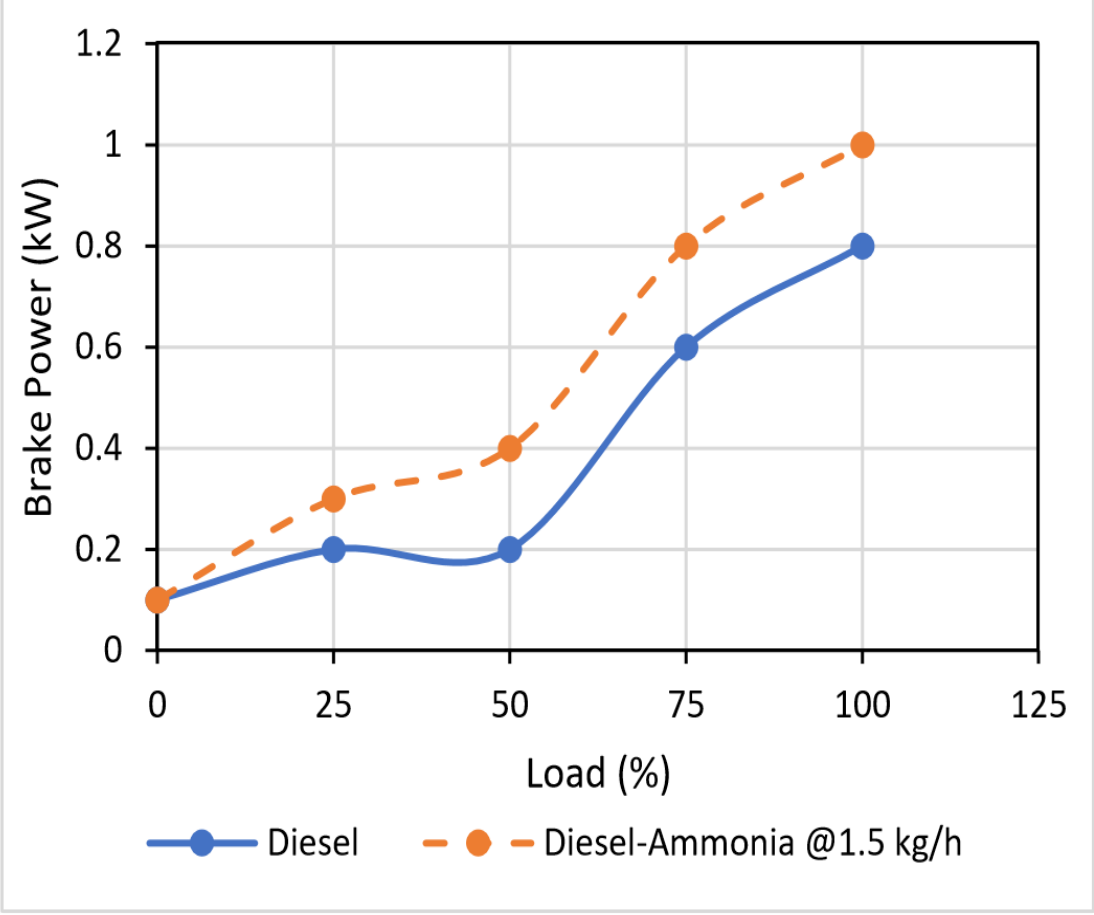


Figure 3: Brake power versus engine load

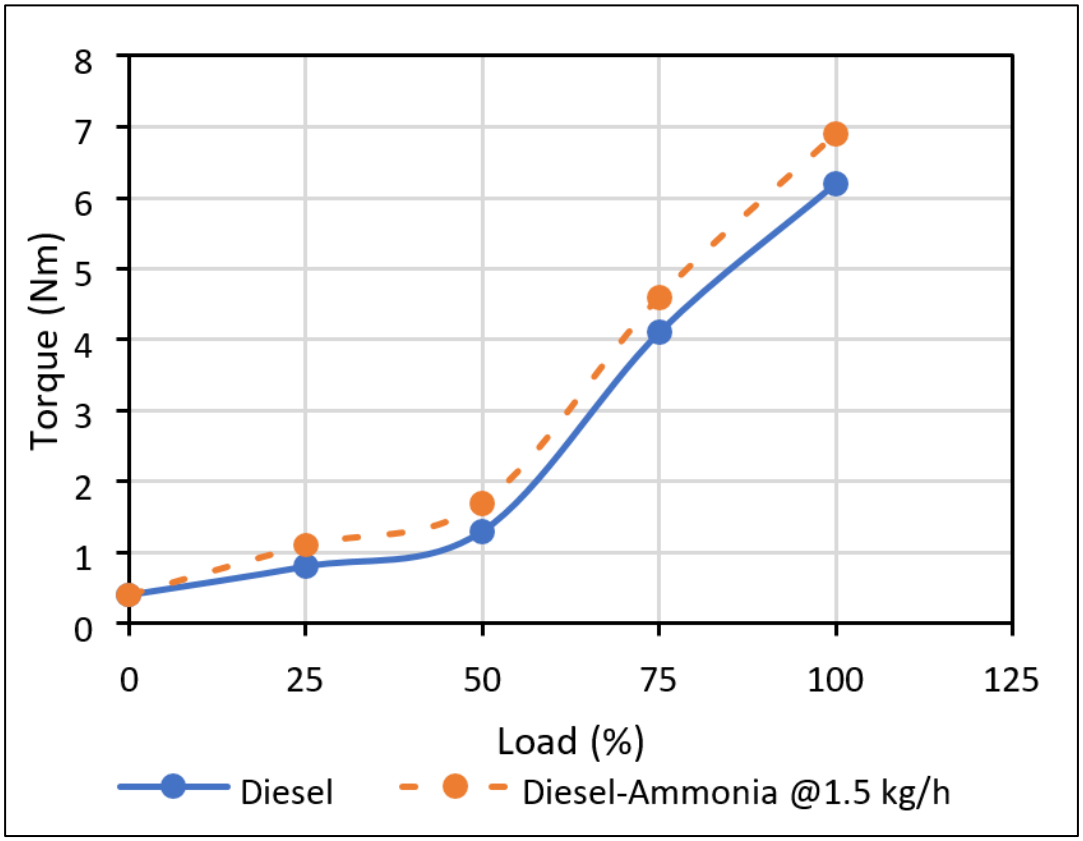


Figure 4: Brake torque versus engine load

Similar trend is observed for the brake torque. With addition of ammonia concentration in diesel fuel at engine 100% load, the brake torque improves by 11.3%. The research work aligns with findings in previous studies that ammonia-diesel dual-fuel systems can achieve stable high-power outputs comparable to diesel fuel. For instance, studies have reported that diesel's high cetane number supports the initiation of combustion, allowing ammonia to contribute to the power output without compromising performance at higher loads [14]. Research by [15] highlighted that diesel's role in dual-fuel setups aided ammonia's ignition, allowing engines to maintain torque levels comparable to dieselonly combustion even as ammonia proportion increased.

Fuel Consumption

The graph of load against fuel consumption for a CI engine fuelled with diesel and ammonia blend with diesel is shown in Figure 5. As the engine load rises, the fuel

consumption increases denoting a normal pattern in CI engines. It is noted that at low loads (0% and 25%), the engine consumed low fuel. However, at higher engine loads from 50% and above, the engine is observed to consume fuel significantly. In a similar trend, the engine fuel consumption for ammonia-diesel fuel increases with engine loads and reduces when compared to when diesel fuel is only utilized. The finding of this research work agrees with previous studies of [16], [17] that blending ammonia with diesel reduced the diesel required per kilowatt-hour, potentially lowering overall fuel consumption in CI engines. The data shows that fuel consumption reduction underscores the efficiency gain from incorporating ammonia into diesel fuel blend.

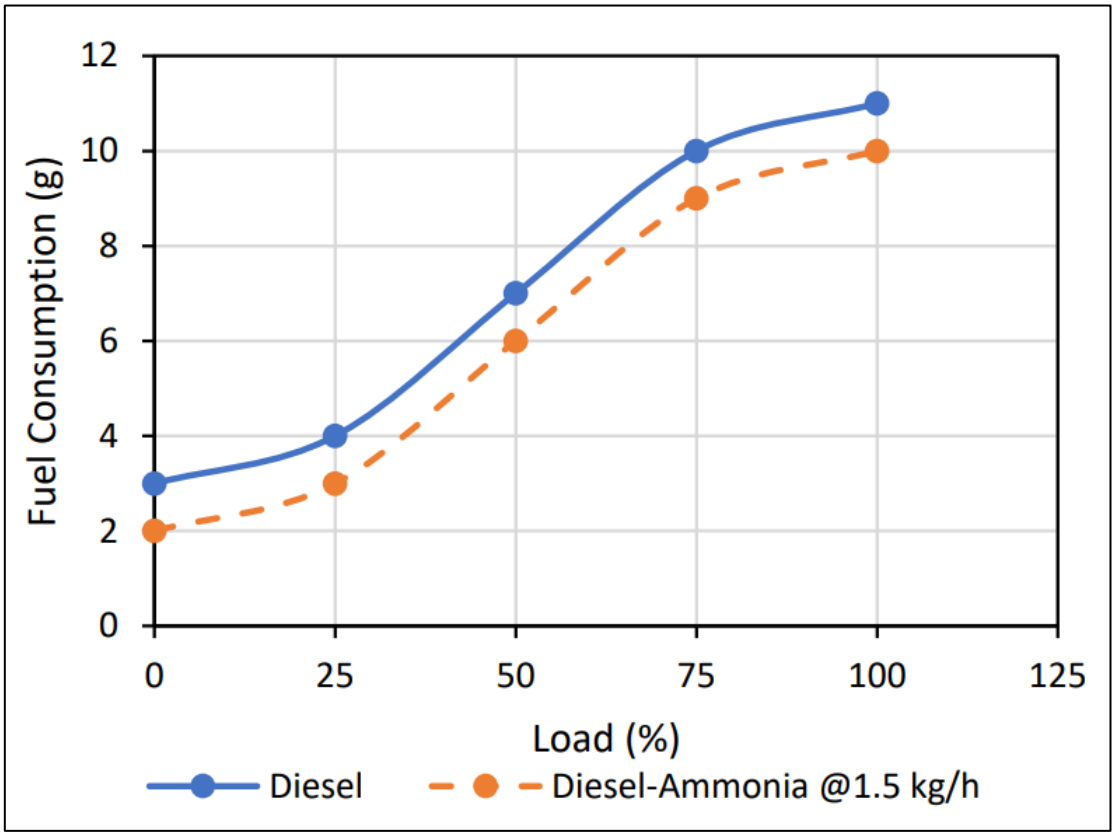


Figure 5: Engine load versus fuel consumption

Emissions Characteristics

The emission of pollutants from a piston engine primarily depends on the type of fuel being burned. In the case of cocombustion of ammonia with diesel fuel leads

to the formation of hydrocarbon (HC), carbon dioxide (CO_2), carbon monoxide (CO), and soot. For the present study, the ammonia concentration in the blend is 20% by energy. The emission characteristics of the fuels are explained below.

Carbon dioxide Emission

The graph of engine load versus carbon dioxide for diesel fuel and ammonia-diesel fuel is presented in Figure 6. It is observed that at low loads up to 50%, both fuels show low carbon dioxide emissions, while at higher loads of 75% and 100%, the CO_2 emissions produced increased. Although, the CO_2 produced when ammonia-diesel blend fuel is utilized in a CI engine significantly reduces across all the loads. The reason for the CO_2 reduction is that ammonia is a carbon-free fuel and substitutes part of the diesel. The result here aligns with the works of [18] and [17] that CO_2 emissions significantly lower in diesel engines running with an ammonia-diesel blend compared to pure diesel operation.

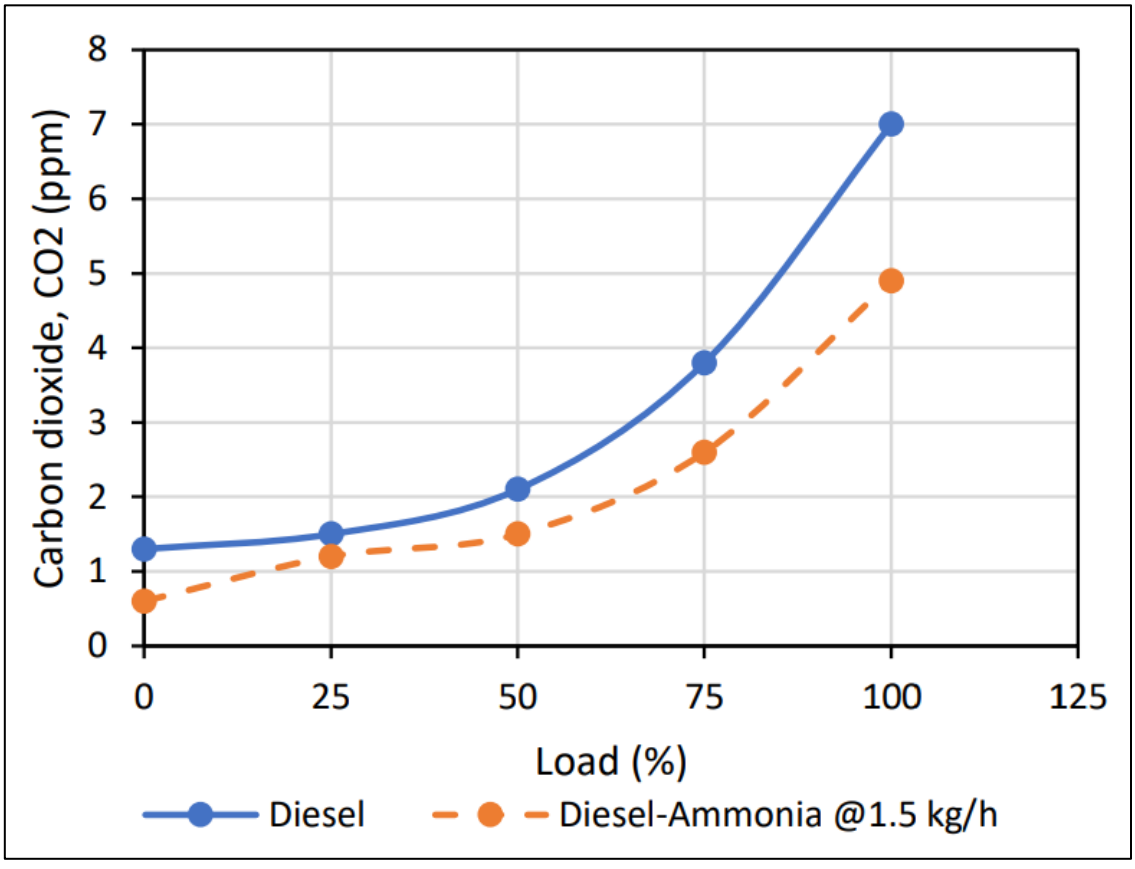


Figure 6: Engine load versus carbon dioxide (CO_2) emission

Carbon Monoxide Emission

Figure 7 shows that CO emission increases with increased load. At idle load (0%), 0.17% of CO emission was recorded when the engine was fuelled with diesel. With increased load to 25%, 50%, 75%, and 100%, the CO emission increased by 8.7%, 13%, 21.7%, and 60.9%, respectively. Similarly, when ammonia concentration was added to diesel, the CO emission increased with increased load but with lesser emission when compared to the diesel emission. The CO emissions were reduced by 23.5%, 21.7%, and 20.7% when compared with the emissions of diesel fuel engine at 0%, 50%, and 100% load, respectively. The reason being that low flame propagation speed of ammonia and high ignition temperature prevented complete oxidation especially at high loads where the fuel mixture is rich. The outcome of the study negates the work of [19] that dual-fuel engines using high ammonia percentages showed increased CO emissions.

Hydrocarbon Emission

The hydrocarbon (HC) emission graph indicates that HC emission increases with engine loads for diesel fuel and ammonia-diesel blend fuel. It is observed at all loads that low HC emission is produced when the engine runs on diesel fuel only. At 0% load, the least HC emission of 23 ppm was produced, while it is 37 ppm at 100%. However, when the engine is operated on ammoniadiesel blend fuel, the HC emission produced is significant for all the loads. 77 ppm and 122 ppm are the HC emissions produced at 0% and 100%, respectively. A similar trend for HC emission was observed by [20] that ammonia presence in diesel contributed to higher unburned hydrocarbons. Valera-Medina et al. [21] also pointed out that ammonia combustion led to higher levels of unburned hydrocarbons due to its slower flame speed especially in high-load operation.

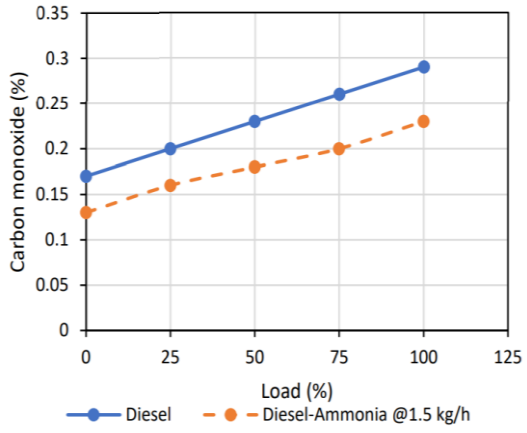


Figure 7: Engine load versus carbon monoxide (CO) emission

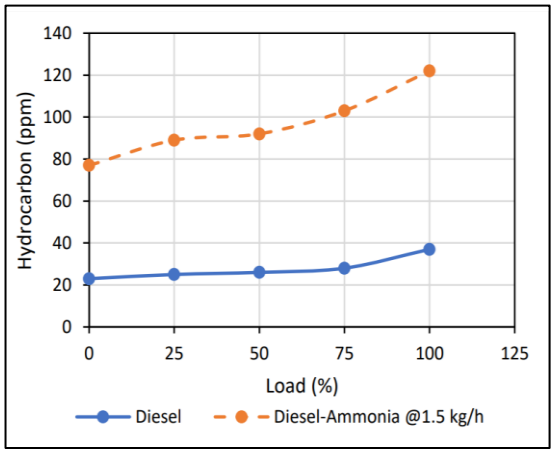


Figure 8: Engine load versus hydrocarbon (HC) emission

Nitrogen Oxide Emission

Figure 9 displays the effect of different loads on nitrogen oxide emission. At low loads up to 50%, NOx emission shows no significant rise when the engine was fuelled with diesel. However, with increased load to 75% and 100%, NOx emission increased significantly to 81 ppm and 167 ppm, respectively. Similarly, with ammonia addition, NOx emissions almost steadily increased and greatly higher at all loads when compared to the diesel fuel only. The reason being that NOx emission formation is driven by both ammonia's nitrogen content and the high combustion temperatures needed to ignite it in a diesel engine, which of course intensifies the production of nitrogen oxides. This result also corroborated the research of [22] that ammonia combustion in high-temperature conditions led to increased NOx emissions.

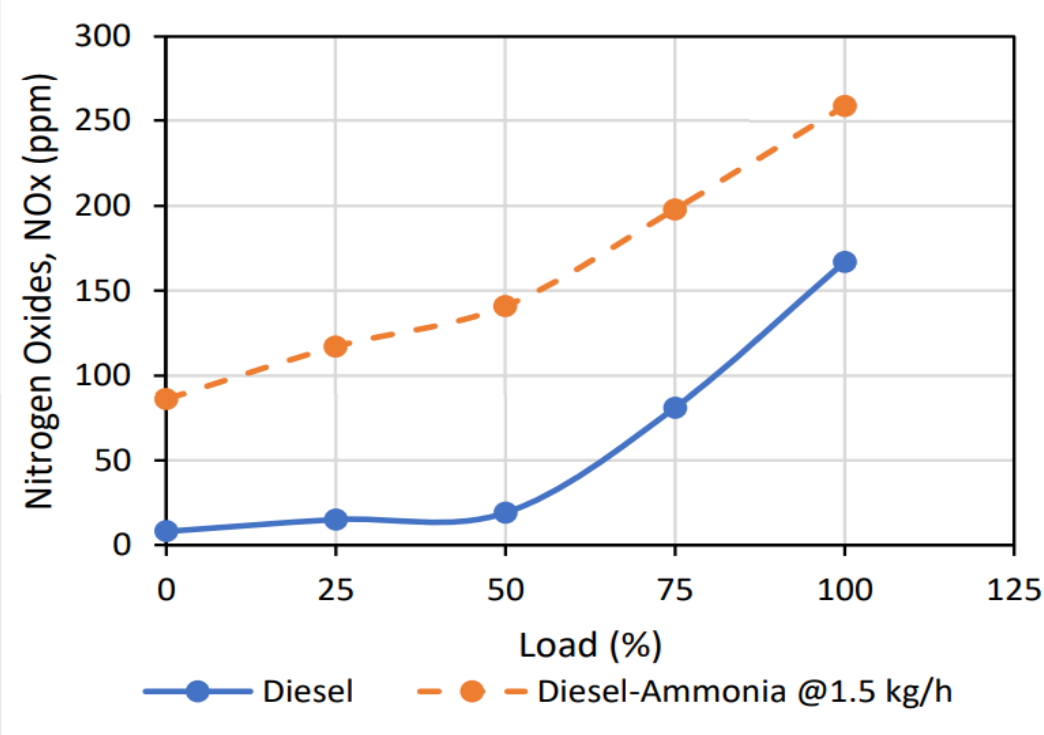


Figure 9: Engine load versus nitrogen oxides (NOx) emission

CONCLUSION

The results of this study reveal that blending ammonia with diesel fuel in compression ignition engines offers significant environmental and performance benefits while presenting some challenges. The ammonia-diesel blend (20%

ammonia) reduces CO_2 emissions and diesel fuel consumption, leveraging ammonia's carbon-free composition and energy contribution. Interestingly, although CO emissions are typically expected to increase with ammonia-diesel blends, they are instead reduced. Additionally, the blend enhances brake power and torque at higher engine loads. However, it increases NO_x and unburned hydrocarbon (HC) emissions due to ammonia's nitrogen content and slower flame propagation. These findings highlight the need for optimized combustion strategies to balance performance and emissions. The study concludes that ammonia-diesel blends are a feasible low-carbon alternative fuel, supporting sustainable energy transitions for transportation and industrial applications. Future research should explore increasing the ammonia concentration and incorporating oxygen gas to improve oxygen supply and further enhance combustion efficiency.

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