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How Methanol-Diesel Fuel Blends Influence the Performance Characteristics of a Compression Ignition Engine

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ABSTRACT

Experimental work was carried out to evaluate the performance, 1combustion, and emission1 properties of ignition engines using different types of diesel fuel at three different speeds (1600, 2000, and 2500 rpm) under three loads (2, 5, and 8 nm). Methanol was mixed with pure diesel fuel at three different levels (9%, 16%, and 24%), named M9, M16 M24, respectively, while pure diesel fuel, named D, was also considered to facilitate a comparison. The performance indicators studied were brake-specific fuel consumption, brake 1thermal efficiency, 1exhaust gas temperature, noise intensity and friction power. Additionally, exhaust gas emissions were analyzed, including CO, CO_2, NOx, and HCI. The results show the possibility of using the M24 fuel type instead of pure diesel fuel without making any modification to the diesel engine, as there is a clear difference in brake thermal efficiency, exhaust gas temperature, noise intensity, and friction power at different loads and speeds compared to pure diesel fuel. We notice an effect due to the triple interaction between fuel type, speed and load, with D recording the highest value at a speed of 1500 rpm1 and a load of 3 nm, as it recorded a clear increase for brake-specific fuel consumption. M24 recorded the highest value at a 1speed of 1500 rpm1 and a load of nm 8 in brake 1thermal 1efficiency. It also recorded a clear 1decrease in exhaust gas emissions CO, NOx, HCL, and exhaust gas temperature as well as noise intensity, while it recorded an increase in CO_2.

1. INTRODUCTION

The progress of human civilization depends to a large extent on transportation, in which internal combustion engines play an important role. Compression ignition (CI) engines provide substantial power to large cars, trucks, ships and other heavy equipment. However, in recent years, after further scientific progress, it has been discovered that internal combustion engines cause great harm as the gases resulting from the combustion of fuel are harmful to human health and living organisms [1]. Many1studies have thus focused on improving the properties of the diesel fuel used in CI engines, such as by using biofuel to increase engine performance and reduce the harmful gases resulting from fuel combustion [2, 3]. Another disadvantage of using biofuel is the increase in carbon deposits in the fuel, which increases the amount accumulating in the engine [4]. The effects of methanol and ethanol as alternatives to fossil fuels have been studied because they contain oxygen, which aids combustion and increases engine efficiency. Notably, the calorific value of biodiesel is less than the calorific value of diesel fuel [5-7]. Researchers have concluded that the kinematic viscosity value of biodiesel is 1.9 to 6.5 mm2/s and the flash point does not exceed 150 degrees Celsius. Other researchers have found that mixing methanol with pure diesel will increase engine efficiency and reduce exhaust gases, including carbon monoxide (CO) [8-11]. Scholars have concluded that incorporating methanol into diesel fuel can enhance combustion efficiency, reduce exhaust emissions, and improve overall engine performance. Researchers have confirmed that diesel fuel is merely a basic criterion for determining ignition capacity when injected into high-temperature air, which is also under pressure within the engine components prepared for ignition [12]. This delays the ignition process. Others have also confirmed that the fuel consumption (BSFC) in pure diesel engines is relatively high, noting that methanol is mixed with diesel [13]. These conditions are due to the high temperature generated by diesel, such that its energy in pure diesel is higher than in biodiesel. Others have noted that brakes and their equivalent heat improve with increasing methanol content, which is also affected by the high oxygen content and the increased viscosity [14]. All of these conditions increase ignition time, maintain. However, BTE tends to decline as engine speed increases, primarily due to the rise in frictional losses, which diminish braking capacity and subsequently reduce thermal efficiency.

On the other hand, BTE increases with higher loads because the rise in braking capacity enhances thermal efficiency. Bhale et al. [15] explained that methanol effectively reduces nitrogen oxide (NOx) emissions and is characterized by rapid combustion, enabling earlier burning and improved thermal efficiency. They also highlighted that methanol possesses a

high flame propagation velocity, which enhances combustion performance. Additionally, methanol exhibits a longer ignition delay period compared to diesel fuel, contributing to improved exhaust emissions in diesel engines. Furthermore, methanol has a higher fuel-to-air equivalent coefficient ratio than diesel, attributed to its molecular oxidation state and inherent oxygen content.

Chu [16] investigated the effects of methanol/diesel fuel blends (M0, M5, M15) on the performance of a ZS195 single-cylinder diesel engine. The results indicated that while adding methanol reduced the engine's driving force, it significantly improved fuel economy. Methanol blends notably decreased diesel smoke and CO emissions. NOx emissions initially increased with the M5 blend but showed an approximate 8% reduction with M15. However, HC emissions rose when engine parameters remained unchanged.

Ciniviz et al. [17] examined the impact of methanol-diesel blends (ranging from 0% to 15% methanol) on a turbocharged, four-cylinder diesel engine. Tests conducted at speeds between 1000 and 2700 rpm revealed that increasing methanol content led to higher brake-specific fuel consumption (BSFC) and NOx emissions while simultaneously reducing brake thermal efficiency (BTE), carbon monoxide (CO), and hydrocarbon (HC) emissions. At 1600 rpm, a 10% methanol blend, compared to pure diesel, resulted in lower power output (47.5 kW vs. 49 kW), increased BSFC (190 g/kWh vs. 169 g/kWh), reduced BTE (30% vs. 33%), and lower CO (0.18% vs. 0.21%) and HC (6.1 ppm vs. 8.02 ppm) emissions, but an increase in NOx emissions (418 ppm vs. 385 ppm).

This study aims to evaluate the performance, combustion characteristics, and emission properties of diesel engines operating on pure diesel fuel (D) and methanol-diesel blends (M9, M16, and M24) at three different speeds (1600, 2000, and 2500 rpm) and under three load conditions (2, 5, and 8 nm). Methanol was blended with diesel at three different concentrations (9%, 16%, and 24%), designated as M9, M16, and M24, respectively, while pure diesel (D) was used as a baseline for comparison.

The results demonstrated a significant interaction between fuel type, engine speed, and load. Pure diesel (D) recorded the highest BSFC value at 1500 rpm under a load of 3 nm, while M24 exhibited the highest BTE value at 1500 rpm under a load of 8 nm. Additionally, M24 showed a considerable reduction in CO, NOx, HC, exhaust gas temperature (EGT), and noise intensity, although it led to an increase in CO_2 emissions.

2. MATERIALS AND METHODS

2.1 Test engine

The experiment aimed to evaluate the performance of a single-cylinder, four-stroke, air-cooled engine.

Table 1. Technical specifications of the engine

Item	Specification
Engine manufacturer	TQ TD 212, UK
Fuel type	Diesel
Maximum power	kW at 3600 rev/min3.5
Maximum torque	nm at 3600 rev/min16
Bore	mm69
Connecting rod length	104 mm
Engine capacity	232 cm^3 or 232 cc.
Compression ratio	22:1

Table 1 presents the specifications of the test engine used in the study. A hydraulic dynamometer was connected to the engine to apply varying loads and measure the braking power.

2.2 Properties of the fuel

Four types of fuel were used in the experiment: diesel, denoted D, and three types of methanol and diesel mixtures. The first type contains 9% methanol and 91% diesel and is denoted MD 9. The second type contains 16% methanol and 84% diesel and is denoted MD 16. The third type contains 24% methanol and 76% diesel and is denoted MD 24. Table 2 shows the specifications of the fuel used.

Table 2. Fuel specification of fuel type, speed, and load on BTE

D	Diesel Fuel	ppm	Part Per Million
M9	9% Diesel, 91% Methanol Blend	rpm	Revolutions per minute
M16	16% Diesel, 84% Methanol Blend	T	Torque
M24	24% Diesel, 76% Methanol Blend	LHV	Minimum calorific value of fuel
BSFC	Brake-Specific Fuel Consumption	CV	Calorific value
BTE	Brake Thermal Efficiency	CO	Carbon monoxide
EGT	Exhaust Gas Temperature	CO_2	dioxide Carbon
FP	Friction Power	NO_X	oxide Nitrogen
BP	Brake Power	UHC	Un-burnt hydrocarbons

2.3 Test system

The test system had a measuring unit that consisted of a graduated tube that was used to measure the amount of fuel consumed over a specific period of time, an engine speed gauge, an exhaust temperature gauge, and a gauge to measure the engine load. This system was connected to a diesel test engine, a hydraulic dynamometer, and a device to analyze the results and data obtained from the ECA100 test engine. Figure 1 shows the test system. A sound level measuring device of the Onsoku type (SM-7) and an exhaust gas testing device of the AIRREX HG-540 type, made in Korea, were used.



Figure 1. (a) Engine control unit, (b) engine block, (c) Gas analyzer device

2.4 Studied characteristics

BSFC was calculated using Eq. (1) [18]:

$$BSFC = \frac{mf}{BP} \quad (1)$$

where, *mf* is, *BP* is brake power and fuel consumption.

Brake power (kW) refers to the engine's output power and can be determined using Eq. (2):

$$BP = \frac{2\pi NT}{60000} \quad (2)$$

The fuel consumption was calculated using Eq. (3):

$$mf = \frac{sfg * 8 * 0.001}{t} * 3600 \quad (3)$$

BTE was calculated from Eq. (4) [19]:

$$\eta bth = \frac{BP}{m * LCV} \quad (4)$$

3. EXPERIMENT SETUP

Four types of fuel were used: D, M9, M16, and M24, at three speed levels (2500, 2000, and 1600 rpm) and three engine load levels (8, 5, and 2 nm) on a four-stroke, single-cylinder, air-cooled diesel test engine. A hydraulic dynamometer was connected to the engine to apply loads and measure the power generated. The engine was initially equipped with the first fuel type, pure diesel (D), which served as the baseline for comparison with the methanol-blended fuels. The engine was operated for 15 minutes to reach the ideal temperature. Once stabilized, the engine speed was gradually set to 1600 rpm with a load of 2 nm by increasing the water flow from the hydraulic dynamometer. After the engine stabilized, fuel consumption, load, and sound level were recorded from the graduated tube. Subsequently, exhaust gas readings were taken using an AIRREX exhaust analysis device, with the inspection tube placed in the engine's external exhaust duct, and the data were recorded. The measurements were repeated three times, and the average values were used to improve accuracy. After completing the readings at the 2 nm load, the load was increased to 5 nm at the same speed of 1600 rpm by adjusting the water flow through the hydraulic dynamometer until the engine stabilized. All steps from the 2 nm load were repeated, and readings were taken at the 5 nm and 8 nm loads. The speed was then adjusted to 2000 rpm, and the same procedures were followed. After completing the measurements for the first fuel type, the fuel tank was emptied and replaced with the second fuel type, M9. The engine was run for 20 minutes to ensure all the previous fuel was purged from the engine. The same steps were followed for the second fuel type, and once those readings were completed, the third fuel type, M16, was tested. Finally, the fourth fuel type, M24, was examined, following the same procedure.

4. RESULTS AND DISCUSSION

Figure 2 illustrates the impact of the triple interaction between fuel type, engine speed, and load on brake-specific fuel consumption (BSFC). The data indicate that BSFC decreases as speed and load increase. A notable distinction is observed for fuel type D, which exhibits the highest BSFC value (0.415 kg/kW) at a speed of 1600 rpm and a load of 2 nm, whereas fuel type M24 achieves a BSFC of 0.105 kg/kW at a speed of 2500 rpm and a load of 8 nm.

The reduction in BSFC with increasing load and speed is primarily attributed to the lower calorific value of methanol, which affects injector pressure based on operating conditions. Additionally, as internal load and speed rise, a greater amount of energy is required to compensate for the additional power generated on the engine shaft, leading to increased fuel consumption. Moreover, higher loads and speeds enhance brake force, further contributing to a decrease in BSFC.

This phenomenon is also influenced by the lower calorific value of the fuel, which increases overall fuel consumption while establishing an inverse relationship with BSFC. For the M24 fuel blend, the observed reduction in BSFC can be attributed to its higher evaporation rate and more efficient combustion characteristics compared to pure diesel, as supported by Hassan et al. [20].

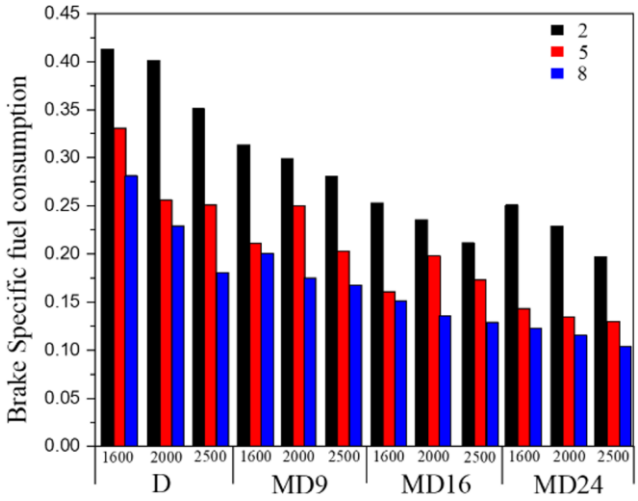


Figure 2. Effects of the interaction between fuel type, different speeds and torque on brake specific fuel consumption

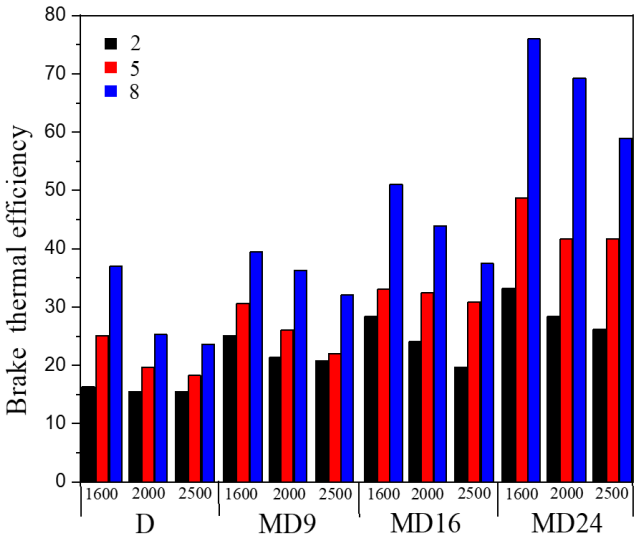


Figure 3. Effect of between the interaction fuel type, speeds and torque on break thermal efficiency

Table 3. Fuel properties

Data	D	M9	M16	M24
Specific gravity at 15.6℃	0.834	0.820	0.818	0.816
API 15.6℃	39.8	39.7	39.9	40.9
Point of operation ℃	69.1	69.7	69.1	68.6
Color (ASTM)	0.8	0.8	0.8	0.8
Spill point ℃	-13	-21	-21	-21
Viscosity at 40℃	2.9	2.7	2.3	1.9
Sulfur wt.%	0.67	0.58	0.58	0.56
Density kg/m^3 at 15.6℃	0.829	0.823	0.821	0.817
Cetane number	56.4	57.2	57.9	58.1
Calorific value KJ/Kg	45786	45679	45664	45482

Figure 3 and Table 3 illustrate the influence of fuel type, engine speed, and load on brake thermal efficiency (BTE), showing that BTE increases with higher loads and lower speeds. Among the tested fuels, M24 exhibits the highest BTE (33.1) at a speed of 1600 rpm and a load of 8 nm, whereas fuel type D records the lowest value (15.2).

The increase in BTE with higher methanol content is primarily due to methanol's superior combustion efficiency, attributed to the abundance of oxygen in its molecular structure compared to pure diesel, which enhances fuel combustion [4]. Another contributing factor is the higher fuel injection pressure and lower viscosity associated with an increased proportion of methanol in the fuel blend, leading to improved atomization and combustion efficiency.

At lower engine speeds, BTE improves due to enhanced fuel evaporation and ignition, as combustion occurs more efficiently at reduced speeds, minimizing friction and increasing both braking capacity and thermal efficiency. Additionally, at higher loads, the increase in braking capacity directly contributes to improved BTE.

Furthermore, the presence of methanol in the fuel blend results in a lower calorific value, which paradoxically enhances BTE by promoting more complete combustion. Blended fuels also generate less heat compared to pure diesel, reducing heat transfer losses and further improving efficiency. These findings align with previous studies [21-25].

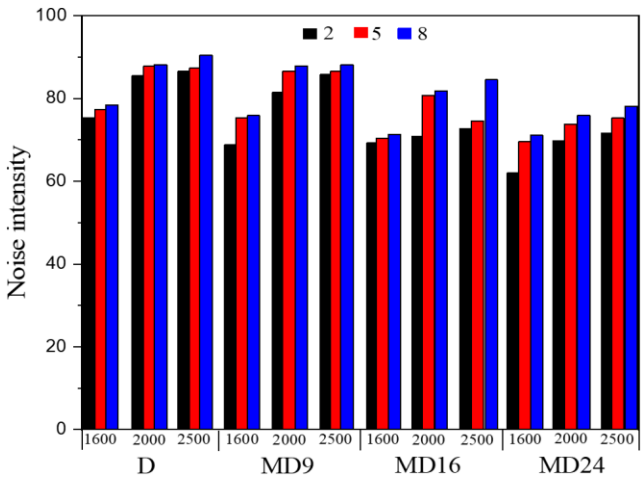


Figure 4. Effect of the interaction between fuel type, speeds and torque on noise intensity

Figure 4 illustrates the impact of fuel type, engine speed, and load on noise intensity. The results indicate that noise intensity decreases as the methanol content in the fuel mixture increases. The lowest noise level (61.42 dB) is recorded for M24 at a load of 2 nm and a speed of 1600 rpm, whereas the highest value (89 dB) is observed for fuel type D at a speed of 2500 rpm and a load of 8 nm.

An increase in noise intensity is noted as both engine speed and load rise. This phenomenon is primarily attributed to the high-speed collision of exhaust gas molecules and the elevated injection pressure within the combustion chamber as engine torque increases. The higher torque demands a greater fuel injection rate to sustain the same power output, leading to a rapid rise in exhaust gas pressure. This pressure surge results in intensified interactions between the waves of emitted gases, thereby amplifying noise levels, as supported by previous studies [26-33].

Figure 5 presents the influence of fuel type, speed, and load on friction power. The data show that friction power increases with higher speeds and loads. The highest friction power (0.42 kW) is recorded for fuel type D at a speed of 2500 rpm and a load of 8 nm, while the lowest value (0.13 kW) is observed for M24 at a speed of 1500 rpm and a load of 2 nm.

The rise in friction power at higher speeds and loads is primarily due to the increase in engine temperature, which causes the expansion of engine components, reducing the time available for cooling. Additionally, the increase in pressure resulting from higher loads further elevates engine temperature and decreases oil viscosity, leading to greater frictional losses.

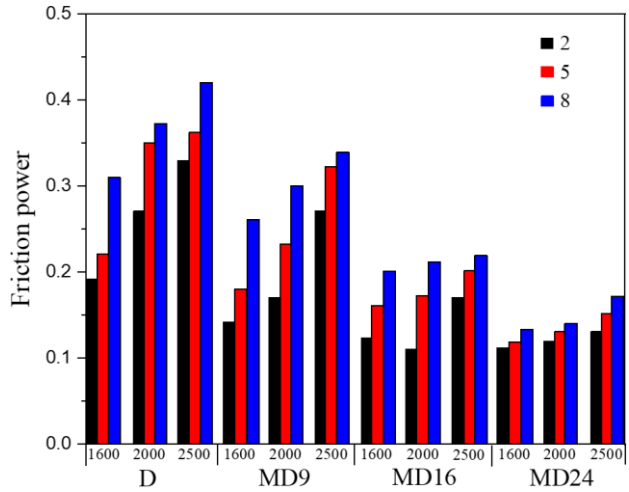


Figure 5. Effect of between the interaction fuel type, speeds and torque on friction power

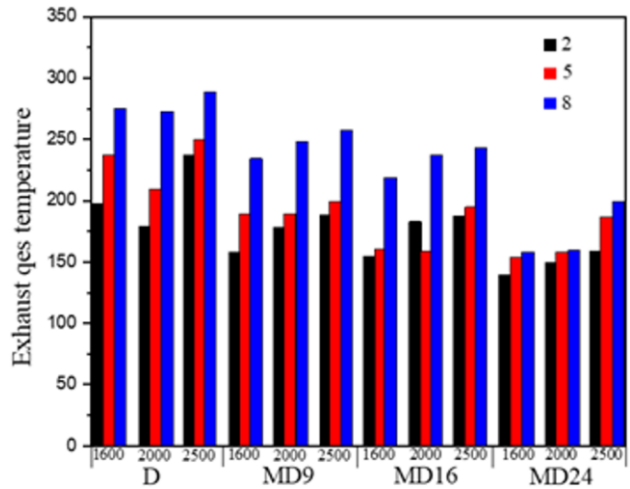


Figure 6. Effect of the interaction between fuel type, speeds and torque on exhaust gas temperature

Figure 6 illustrates the influence of fuel type, engine speed, and load on exhaust gas temperature. A noticeable decrease in exhaust gas temperature is observed for M24 and M16 compared to fuel type D. Specifically, M24 records the lowest temperature (136.5℃) at 1600 rpm and 2 nm, while D exhibits the highest value (273.46℃).

The reduction in exhaust gas temperature is primarily attributed to the higher methanol content in the fuel blend. Methanol has a lower calorific value and contains ample oxygen, which enhances combustion efficiency while minimizing heat loss within the engine cylinder. Additionally, methanol's higher evaporation rate and volatility compared to pure diesel enable it to absorb more heat from the engine cylinder, further contributing to the decrease in exhaust gas temperature. Conversely, at higher engine speeds and loads, exhaust gas temperature increases due to the greater fuel consumption required to maintain the same power output.

Figure 7 shows the effect of fuel type, speed and load on CO emission. The highest value (0.059) is recorded for D at 1600 rpm and 2 nm, while the lowest value (0.005) is found for M24 at 2500 rpm and 8 nm. The decrease in CO is attributed to the increase in the percentage of methanol in the mixture, as methanol contains a high percentage of oxygen. This penetrates completely and delays ignition, which leads to an increase in the heat emitted in the area before the mixture burns, thus reducing the ignition period in the combustion area and causing a decrease in CO.

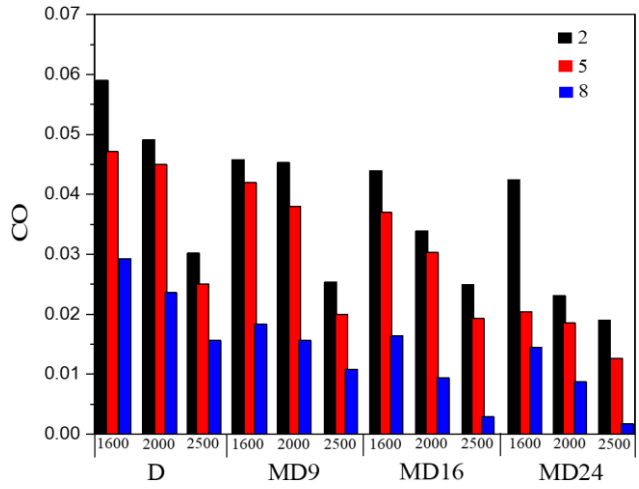


Figure 7. Effect of the interaction between fuel type, speeds and torque on CO

Figure 8 shows the effect of fuel type, speed and load on CO_2 emission. CO_2 increases with the increase in the percentage of methanol at high speeds and loads. The highest value (10.98) is recorded for M24. This is attributed to the increase in methanol in the mixture quantity; the high percentage of O_2 results in complete combustion and reduces the phenomenon of decomposition as a result of the decrease in temperature, producing an increase in CO_2. Methanol is characterized by a low cetane number, which leads to a long ignition period, as it delays the fuel injection period into the combustion chamber, causing an increase in CO_2.

Figure 9 illustrates the effects of fuel type, engine speed, and load on NOx emissions, which decrease as the methanol content in the fuel blend increases. The lowest NOx emission level (57.2 ppm) is recorded for M24 at 2500 rpm and 2 nm, while the highest value (549.89 ppm) is observed for fuel type D.

This reduction in NOx emissions can be attributed to methanol's lower calorific value, viscosity, and fuel density, along with its high cetane number, all of which influence the ignition process. These properties contribute to ignition delay, resulting in a lower peak combustion temperature and reduced latent heat of vaporization, ultimately leading to lower NOx formation. On the other hand, nitrogen oxide emissions tend to increase at maximum loads due to the increased energy injection required to maintain engine life. This incomplete combustion leads to a significant increase in nitrogen oxide emissions.

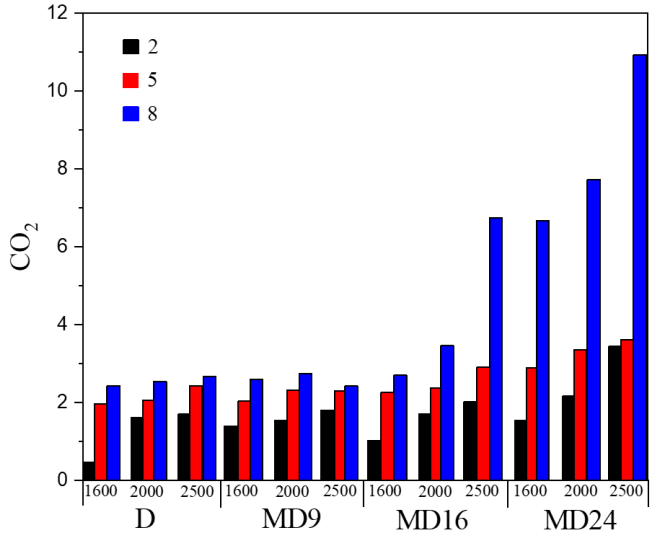


Figure 8. Effect of the interaction between fuel type, speeds and torque on carbon dioxide

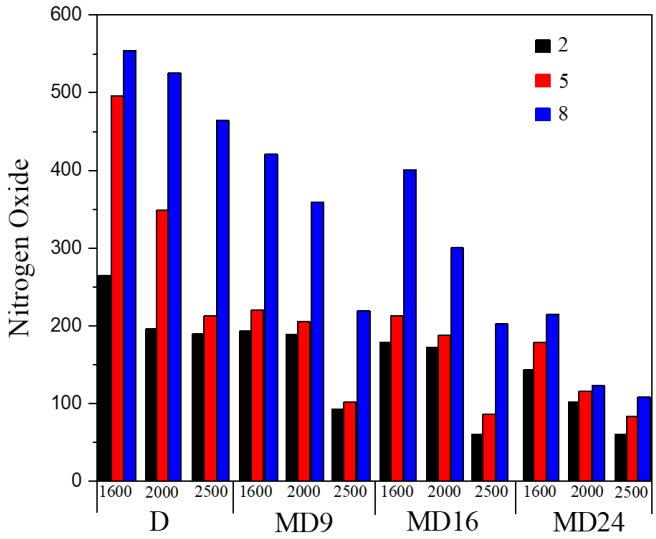


Figure 9. Effect of the interaction between fuel type, speeds and torque on nitrogen oxide

Hydrocarbon (HCI) emissions are affected by the type of fuel used, the engine speed generated, and the applied load. The desired results from HCI are low due to the increased methanol content in the fuel, and this decrease increases with the required engine speed at low loads, as shown in Figure 10. When the engine rpm was 2,500, the HCI value was very low, due to the high methanol content in the fuel. Combustion performance is improved by the increased oxygen content.

The oxygen available in the combustion chamber provides optimal combustion if the percentage is high, and vice versa.

On the other hand, the volume of air inside the combustion chambers increases with increasing engine speed, which in turn leads to the complete combustion of both fuel and air. As for the loads, they lead to an increase in the (HCl) ratio, especially if its value is high, and the reason for its increase is the decline in the intensity of ignition, which in turn leads to a slowdown in ignition, causing a decrease in the combustion rate, resulting in hydrochloric acid emission processes.

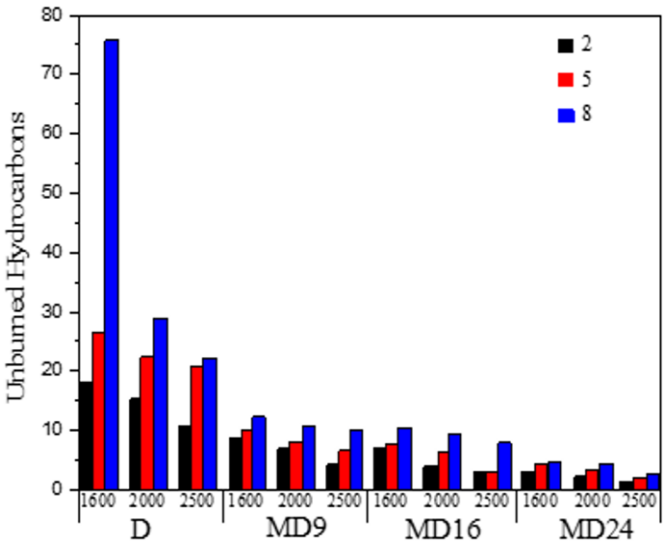


Figure 10. Effect of the interaction between fuel type, speeds and torque on unburned hydrocarbons

5. CONCLUSIONS

A greater methanol-to-diesel ratio ultimately affects carbon dioxide (CO_2) emissions and brake thermal efficiency (BTE) while lowering exhaust gas temperature, noise intensity, frictional force, brake-related fuel consumption (BSFC), and emissions of carbon monoxide (CO) and nitrogen oxides (NOx). In addition to increased CO_2 emissions, greater engine speeds also result in higher exhaust gas temperature, BSFC, frictional force, noise intensity, BTE, CO, and NOx emissions. In a similar vein, raising engine load from 2 to 8 nm lowers CO and BSFC emissions while increasing exhaust gas temperature, frictional force, CO_2 and NOx emissions, and noise level. The M24 blend attains higher BTE at 1,500 rpm, but pure diesel at 2,500 rpm and 8 nm shows the maximum noise intensity, frictional force, exhaust gas temperature, CO, CO, NOx, and unburned hydrocarbons.In addition to increased CO_2 emissions, greater engine speeds also result in higher exhaust gas temperature, BSFC, frictional force, noise intensity, BTE, CO, and NOx emissions. In a similar vein, raising engine load from 2 to 8 nm lowers CO and BSFC emissions while increasing exhaust gas temperature, frictional force, CO_2 and NOx emissions, and noise level. A greater methanol-to-diesel ratio ultimately affects carbon dioxide (CO_2) emissions and brake thermal efficiency (BTE) while lowering exhaust gas temperature, noise intensity, frictional force, brake-related fuel consumption (BSFC), and emissions of carbon monoxide (CO) and nitrogen oxides (NOx).

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