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Experimental investigation of the impact of methanol-diesel blends on diesel engine emissions and performance

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In this study, the impact of methanol-diesel fuel blends on the performance and exhaust emissions of a four-cylinder, four-stroke, direct injection, turbocharged diesel engine was experimentally analyzed. This investigation was conducted in response to increasingly strict regulations on exhaust emissions for newly manufactured diesel engines. The blends used had methanol content ranging from 0% to 15% with 5% increments. Engine performance tests were conducted on a dynamometer, varying engine speed from 1000 min^{-1} to 2700 min^{-1}. The results reveal that although all fuels exhibit increased power output with rising engine speed, incorporating methanol results in a power reduction of approximately 4% for M5, 9% for M10, and 13% for M15 compared to pure diesel. Conversely, the brake specific fuel consumption (BSFC) improves with methanol addition, decreasing by roughly 5%, 10%, and 14% for M5, M10, and M15, respectively, which suggests enhanced combustion efficiency. Furthermore, carbon monoxide (CO) emissions drop significantly with higher methanol content, showing reductions of about 13%, 27%, and 40% for the M5, M10, and M15 blends, respectively, relative to standard diesel. Balancing the observed trade-offs between power loss and efficiency gains, the 10% methanol blend (M10) emerges as the optimal fuel mixture, offering substantial improvements in fuel economy and emission reductions with only a moderate decrease in engine power.

Key words: *diesel engine, blending fuel, engine emission, thermodynamic analysis, heat engine*

1. Introduction

Compression ignition (CI) engines are widely utilized in automotive, industrial, and transportation sectors due to their high fuel conversion efficiency and operational simplicity. The extensive applications of CI engines have led to a growing demand for petroleum-derived fuels. This increased demand, combined with declining petroleum reserves, has caused fuel costs to rise significantly. Additionally, the exhaust emissions from these engines primarily soot and nitrogen oxides (NO_x) pose serious environmental and health hazards [18]. Global efforts are intensifying to reduce diesel engine emissions, particularly those involving soot, carbon monoxide (CO), hydrocarbons (HC), and NO_x.

In order to reduce exhaust emissions, much recent research on internal combustion engines (ICEs) has focused on optimizing engine characteristics, including atomization ratios, valve timing, and injection timing. In parallel, research into renewable fuels, such as methanol, ethanol, hydrogen, and biodiesel, has accelerated due to concerns over fossil fuel depletion and environmental impacts. Methanol, in particular, can be synthesized from various sources, including coal, oil, natural gas, biomass, wood, landfills, and even seawater.

However, standard internal combustion engines, especially CI engines, have specific fuel system requirements that limit the direct use of renewable fuels [4]. To address this, renewable energy sources are often blended with fossil fuels, enabling the use of existing ICE technology while reducing both costs and environmental impacts associated with petroleum-based fuels. The addition of methanol to diesel fuel in CI engines is a notable example of such an approach, which has been extensively researched. The dual-fuel operation of methanol and diesel offers several advantages over conventional diesel fuel [16]. As for the choice of methanol over other alcohols like ethanol or butanol, it should be explained based on factors such as methanol's lower molecular weight, higher oxygen content, and its established compatibility with diesel engines. Methanol is often preferred due to its ability to reduce particulate matter and carbon monoxide emissions more effectively than other alcohols. Moreover, methanol's availability, cost-effectiveness, and the extensive research supporting its use in diesel fuel blends make it a favorable option. A comparison to ethanol and butanol, highlighting their limitations (such as higher energy consumption in ethanol production or the higher viscosity of butanol), would further justify the selection of methanol in this context. These benefits include a higher stoichiometric air-to-fuel ratio, which promotes efficient combustion, and high oxygen content along with a favorable hydrogen-to-carbon ratio and low sulfur levels, which further reduce pollutant emissions. Methanol also has a greater latent heat of vaporization, enhancing the cooling effect within the engine. This effect, combined with methanol's rapid evaporation when blended with diesel, reduces the work required during the compression stroke. Overall, these factors lead to improved combustion efficiency, with decreased smoke and soot emissions [13].

The following is a summary of the potential benefits and drawbacks of using methanol as a fuel for compression ignition engines. Methanol can be introduced into diesel engines either by injecting it into the intake air or by blending it with diesel fuel, as explained by Zhang and Balasubramanian [19]. The simplest method is to use methanol in CI engines as a mixture with diesel fuel; however, phase separation is a significant issue in such blends. This problem can be mitigated by adding a solvent, while an ignition enhancer, like diethyl ether, can be used to increase the cetane number of the blend. When methanol concentrations in the blend are low, no engine or fuel system modifications are required for its use [1]. On the other hand, the fumigation method, which involves injecting methanol into the intake air via low-pressure injectors, requires slight engine modifications. This method allows for the use of higher methanol concentrations and offers flexibility in adjusting the diesel/methanol ratio according to varying operating conditions, unlike premixed fuel, which operates at a fixed diesel/methanol ratio.

The increased emissions of carbon monoxide and hydrocarbons resulting from the fumigation of methanol present a significant drawback to this approach. However, diesel oxidation catalysts (DOC) can be used to oxidize certain emissions, including HC and CO, mitigating some of these adverse effects [20]. Given methanol's potential to simultaneously address air pollution and reduce reliance on petroleum, many researchers have studied the impact of methanol-blended diesel fuel on ICE exhaust emissions. Cheng et al. [3] examined the effects of fumigated methanol on engine performance, exhaust emissions, and particulates. They reported that methanol was injected and fumigated at engine loads of 10%, 20%, and 30% under various operating conditions. The experimental findings indicated that while fumigated methanol generally reduced brake thermal efficiency (BTE), it increased BTE at low loads, except at the maximum load of 0.67 MPa. The emissions of CO, nitrogen oxides, and unburned hydrocarbons (UHC) rose considerably with fumigated methanol.

Çanakçi et al. [4] conducted a series of research to investigate the effects of injection pressure on engine performance, exhaust emissions, and combustion parameters using methanol-blended diesel fuel with 5% methanol increments. By adjusting shim numbers, experiments were conducted at injection pressures of 180, 200, and 220 bar. The results showed that increasing methanol content led to rises in brake-specific fuel consumption, brake-specific energy consumption, combustion efficiency, smoke numbers, and emissions of CO and UHC. Additionally, the heat release rate, peak cylinder pressure, and emissions of NO_x and carbon dioxide also increased.

Yao et al. [18] explored the effects of diesel-methanol compound combustion (DMCC) on diesel engine combustion. Experiments were performed on a four-cylinder CI engine modified for DMCC, comparing exhaust emissions from pure diesel operation and DMCC operation, both with and without an oxidation catalyst. The findings indicated that DMCC could reduce soot and NO_x emissions compared to a standard diesel engine, but increased HC and CO emissions. However, using DMCC in combination with an oxidation catalyst reduced emissions of CO, HC, NO_x, and soot. According to Bayraktar [1], a 10% methanol blend (DM10) is the most suitable choice for CI engines in terms of performance. This blend incorporates varying proportions of methanol and achieves performance improvements of up to 7% without necessitating alterations to the engine or fuel system. To prevent phase separation, 1% dodecanol was added to each blend, allowing methanol content to be adjusted from 2.5% to 15% at increments of 2.5%. Tests were conducted at compression ratios of 19, 21, 23, and 25 and engine speeds between 1000 and 1600 min^{-1}.

Eyal et al. [5] experimentally validated the Reforming-Controlled Compression Ignition (RefCCI) concept, combining low-temperature combustion with thermochemical recuperation. Results showed a 4–9% improvement in thermal efficiency over diesel mode, reduced NO_x and particle emissions, and lower CO emissions at higher loads. The study confirmed previous numerical findings and provided insights into the effects of fuel injection timing and reactivity. Stępień [17] presents a comprehensive review of ammonia's potential as a fuel for internal combustion engines. The study critically analyzes ammonia's physicochemical and functional properties, highlighting challenges in mixture formation and combustion in both spark-ignition (SI) and compression-ignition engines. The necessity of adding small amounts of other fuels to promote combustion is emphasized. The article also addresses emission-related issues and the negative impact of ammonia and its combustion products on engine lubricants, underscoring the need for specially formulated lubricating oils for ammonia-fueled engines. Laskowski et al. [8] investigated the impact of ambient temperature on cold-start emissions in passenger cars and light-duty vehicles, in light of updated RDE test procedures by the European Commission. Using COPERT software and WLTP-based tests, simulations were conducted across temperatures ranging from −10°C to +20°C. The study modeled emissions of CO_2, N_2O, CH_4, NO_x, NMVOC, VOC, TSP, and PN. Results revealed that ambient temperature significantly influences the levels of all these pollutants during cold-start conditions. Chao et al. [2] also studied a blend containing up to 15% methanol in diesel to assess emissions in a six-cylinder, naturally aspirated, direct injection diesel engine. Using both transient and steady-state tests, they observed that increasing methanol content reduced NO_x emissions but increased CO and HC emissions. Results on particulate matter (PM) were variable, with emissions fluctuating depending on operational conditions.

In this investigation, dual-fuel operation with methanol and diesel was selected as a promising approach to improve combustion efficiency and reduce air pollution. Based on a review of dual-fuel literature, the blending method was chosen for its operational simplicity and minimal impact on engine performance characteristics. Therefore, experiments were conducted on a four-cylinder, turbocharged, direct-injection diesel engine to analyze the impact of diesel-methanol blends (0%, 5%, 10%, and 15% methanol) on engine performance and emissions. The findings were evaluated and interpreted, leading to specific recommendations on the application and outcomes of dual-fuel operation in internal combustion engines.

2. Experimental setup and procedure

This investigation focused on the "4DT 39T/185B-217299" turbocharged diesel engine, manufactured by TUMOSAN in Konya, Turkey. The engine used in the study is a four-cylinder, four-stroke, direct-injection model with a 3.908-liter displacement, a 17:1 compression ratio, water cooling, and turbocharging. Table 1 provides the engine's general specifications. A hydraulic dynamometer, connected to the engine's shaft, was employed to apply load, measure output torque, and calculate power.

Table 1. Engine specification

Parameter	Specification
Engine model	4DT 39T/185B-217299
Manufacturer	TUMOSAN, Konya, Turkey
Engine type	Turbocharged diesel engine
Cylinder configuration	Four-cylinder
Stroke cycle	Four-stroke
Fuel injection type	Direct Injection
Displacement volume	3.908 liters
Compression ratio	17:1
Cooling system	Water cooling
Measurement instrumentation	Hydraulic dynamometer
Dynamometer load determination	Load sensor
Output torque measurement	Hydraulic dynamometer
Engine speed measurement	Rotation sensor (on dynamometer)
Fuel flow rate measurement	Calibrated burette and stopwatch

A rotating sensor installed on the dynamometer was used to detect engine speed, and a load sensor was used to calculate the dynamometer load. Fuel volumetric flow rate was measured using a calibrated burette and a stopwatch.

An Italo Plus Spin exhaust emission analyzer monitored exhaust emissions, including CO_2, CO, HC, and NO_x, with the analyzer calibrated using zero gas and standard gases prior to each experiment.

Methanol and Euro-diesel were the primary fuels in this investigation, and their main characteristics are listed in Table 2. Standard diesel engine (SDE) tests were conducted in accordance with Turkish Standards 1231 (TS-1231), based on the results, which correspond with Euro 4 standards on-road engines. Before beginning the testing procedures. OPET, located in Istanbul, Turkey, supplied the Euro diesel, and 99% pure methanol was sourced from a commercial supplier.

Table 2 details the device's specifications

Parameter	Details
Device name	Italo plus spin exhaust emission analyzer
Measured emissions	CO_2, CO, HC, NO_x
Calibration method	Zero gas and standard gases
Primary fuels	Methanol and Euro-diesel
Testing standard	Turkish standards 1231 (TS-1231)

The diesel fuel used was Eurodiesel, a standard grade commonly available in European markets, characterized by a density of approximately 0.83–0.85 g/cm³, a viscosity ranging from 2.0–4.0 mm²/s at 40°C, and a cetane number between 50 and 55, which ensures optimal ignition characteristics for compression-ignition engines. The lower heating value (LHV) of Eurodiesel is around 35.8–36.5 MJ/dm³. The methanol used in this study was of technical grade, with a purity of ≥ 99.8%, a density of about 0.791 g/cm³ at 20°C, a viscosity of 0.544 mm²/s at 20°C, and an LHV of 19.9 MJ/kg, as shown in Tables 3 and 4 in detail.

The test fuels, labeled SDE, M5, M10, and M15, contained 0%, 5%, 10%, and 15% methanol, blended with 100%, 95%, 90%, and 85% diesel fuel, respectively. To ensure a homogeneous mixture and prevent phase separation, the blends were prepared immediately before testing, with a mixer installed in the fuel tank. Testing was conducted under full load and steady-state conditions across ten different engine speeds, ranging from 1000 to 2700 min⁻¹. Throughout the experiment, data were collected on engine coolant temperature, air mass flow rate, and exhaust emissions, including CO, CO_2, UHC, and NO_x. All data were recorded after the engine reached a stable state, with continuous measurement of gaseous emissions over five minutes, displaying the average results. For consistency, the steady-state tests were repeated.

Table 3. Physicochemical properties of diesel fuel

Properties	Value	Unit
Density @ 15°C	838	kg/m³
Kinematic viscosity @ 40°C	2.6	mm²/s (cSt)
Cetane number	50	–
Lower heating value	45	MJ/kg
Flash point	60	°C
Boiling range	180–360	°C
Sulfur content	< 15	ppm
Oxygen content	0	wt%
Carbon content	85.5	wt%
Hydrogen content	13	wt%

Table 4. Physicochemical properties of methanol (CH_3OH)

Properties	Value	Unit
Density @ 20°C	791	kg/m³
Kinematic viscosity @ 20°C	0.60	mm²/s (cSt)
Cetane number (effective)	6	–
Lower heating value	20	MJ/kg
Flash point	11	°C
Boiling point	64.7	°C
Oxygen content	50	wt%
Carbon content	38.5	wt%
Hydrogen content	12.6	wt%

3. Experimental results

The study provides comprehensive results on exhaust emissions, including NO_x, HC, CO, and CO_2, as well as engine performance metrics such as power, torque, brake-specific fuel consumption (BSFC), and brake thermal efficiency (BTE). Figure 1 illustrates the fluctuations in power output at various engine speeds under full load when using dual-fuel strategies.

Figure 2 displays BSFC across engine speeds, where BSFC, defined as the ratio of fuel mass consumption to braking power, reflects fuel efficiency. According to Fig. 3, methanol has the lowest lower heating value of 20.27 MJ/kg, while diesel fuel has the highest at 42.74 MJ/kg. Figure 4 shows CO emissions at maximum load for different engine speeds, with CO percentages recorded at maximum torque (1600 min⁻¹) for M10, M15, M5, and SDE as 14%, 18%, 19%, and 21%, respectively.

Figure 5 presents the NO_x emission variations for diesel fuel and methanol-diesel blends across engine speeds, while Fig. 6 shows the CO_2 emission behavior for these blends. At full load and 1600 min⁻¹, the maximum CO_2 values for

M15, M10, M5, and SDE were 7.91%, 8.1%, 7.88%, and 7.15%, respectively, with CO_2 increasing as methanol content in the blend rose. Figure 7 illustrates HC emissions for both diesel and fuel blends, with emissions at maximum torque (1600 min^{-1}) reduced by 7.15, 6.1, and 5.85 ppm for M5, M10, and M15, respectively, compared to SDE. The experimental results are analyzed across four subsections, each providing interpretations based on maximum torque values as the baseline for graphical analyses. These interpretations offer insight into the influence of fuel blends on engine performance and emissions, comparing outcomes for each parameter at peak torque to better understand the effectiveness of dual-fuel strategies under optimal engine load conditions.

3.1. Engine power

As shown in Fig. 1, the power values for the M5, M10, and M15 fuel blends are lower than those of conventional diesel, with the power reduction becoming more pronounced as the methanol content in the blends increases. This variation in power is attributed to changes in the fuel's physical properties, such as its density and lower calorific value. The densities of M5, M10, and M15 are 0.8375, 0.835, and 0.8325 kg/dm^3, respectively, which are slightly lower than that of standard diesel fuel (SDE). As the density decreases, the calorific value of the fuel also declines in a similar manner. A closer analysis of Figure 1 reveals two key observations. First, the engine power output decreases as the methanol content in the fuel blend increases. Second, this power reduction does not directly correlate with the methanol concentration in the blend. For instance, at an engine speed of 1600 min^{-1}, the power drop for M15 is five times greater than that of M10, but at 2700 min^{-1}, the difference is minimal. This suggests that at higher engine speeds, the shorter combustion duration requires more methanol to maintain performance. Therefore, it can be concluded that engine speed intervals in typical operating conditions should be carefully considered when selecting the appropriate fuel blend. For example, while M15 is advantageous at higher engine speeds due to its exhaust emission characteristics and relatively minimal power loss compared to SDE, M5 is more suitable for lower engine speeds, as its power output closely matches that of SDE.

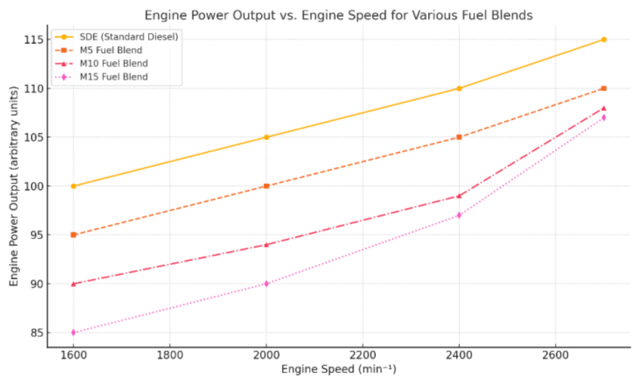

Fig. 1. The engine power output at various engine speed for different fuel blends (SDE, M5, M10, and M15)

3.2. Brake specific fuel consumption

Figure 2 demonstrates that increasing the methanol content in the fuel blend reduces its lower heating value, which in turn leads to higher brake specific fuel consumption. For example, at 1600 min^{-1}, the BSFC values for SDE, M5, M10, and M15 are 280, 220, 200, and 191 g/kWh, respectively. The figure shows that pure diesel fuel exhibits the highest BSFC among the various fuel mixtures. However, at higher engine speeds, the differences in BSFC values between the fuel blends become smaller due to the shorter combustion duration. This can be explained by the fact that methanol molecules contain oxygen atoms, and an increase in methanol content raises the overall oxygen concentration in the fuel blend. The rapid combustion of methanol and the abundance of oxygen enhance the combustion temperature, positively influencing the combustion process. As a result, at higher engine speeds, the BSFC values of the methanol blends approach those of pure diesel fuel.

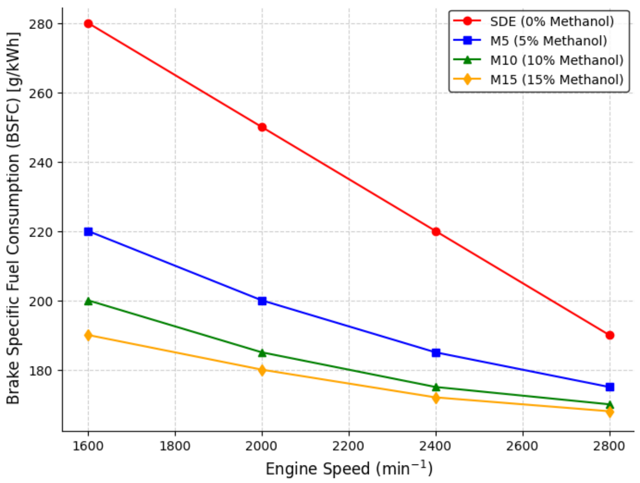

Fig. 2. The brake specific fuel consumption of methanol content in the fuel blends at various engine speeds

3.3. Brake thermal efficiency

Figure 3 illustrates the influence of methanol content on the brake thermal efficiency of a compression ignition engine operating at a constant engine speed of 1600 min^{-1}.

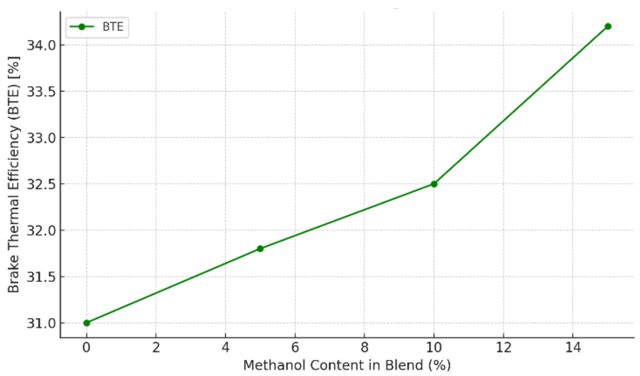

Fig. 3. The effect of methanol content in the fuel blends on brake thermal efficiency at an engine speed of 1600 min^{-1}

As shown, BTE increases progressively with higher methanol percentages in the fuel blend. At 0% methanol (pure diesel), the BTE is approximately 31.0%. With the addition of 5% methanol, the BTE rises to around 31.8%, and further increases to 32.5% and 34.2% at 10% and 15% methanol content, respectively. This steady improvement in BTE can be attributed to several factors. First, methanol has a higher latent heat of vaporization and contains inherent oxygen, both of which enhance the combustion process by promoting more complete and cleaner burning of the fuel-air mixture. Additionally, methanol's higher vaporization rate leads to improved air-fuel mixing, which contributes to more efficient heat release. These combustion-enhancing properties of methanol help offset the energy deficit caused by its lower heating value, resulting in improved thermal conversion efficiency.

3.4. Exhaust emissions

Blending methanol with diesel fuel can help improve emissions from diesel engines by promoting a leaner operation. This is due to methanol's partially oxidized state and its oxygenated nature, which provide a higher stoichiometric fuel-to-air ratio compared to diesel fuel. The lighter operation resulting from this blend may lead to improvements in engine performance metrics (Sayin et al. [16]). Furthermore, the physical and chemical properties of methanol, such as its density, lower heating value, flame speed, and other characteristics, play a significant role in influencing combustion. Exhaust gas measurements taken during experiments at various engine speeds and full load conditions under steady state were recorded and analyzed to assess the effects of the fuel blend.

3.5. Carbon monoxide emissions

Carbon monoxide is a colorless, odorless, and toxic gas that must be controlled due to its harmful effects. CO is produced from the incomplete combustion of fuel and is emitted directly from the tailpipes of moving vehicles. In a perfect combustion process, carbon (C) combines with oxygen (O_2) to form carbon dioxide, but in incomplete combustion, insufficient oxygen results in the formation of CO [4]. The results of this study indicated that increasing the methanol percentage in the fuel blends led to a reduction in CO concentrations in the exhaust emissions. This improvement is attributed to the higher oxygen content of methanol, which enhanced the combustion process. For standard diesel (SDE), CO emissions decrease by approximately 33.3%, dropping from 450 ppm to 300 ppm. In comparison, the M5 fuel blend shows a 31.6% reduction (from 380 ppm to 260 ppm), while the M10 blend exhibits a 30.4% decrease (from 320 ppm to 220 ppm). The M15 blend, containing the highest methanol content, achieves the smallest relative reduction of 26.7%, with emissions declining from 240 ppm to 176 ppm.

Despite the varying reduction rates, the data confirm that higher methanol content consistently results in lower CO emissions across all engine speeds, due to the oxygen-enriched nature of methanol, which promotes more complete combustion. However, the impact of increasing methanol content on CO reduction diminishes at higher methanol concentrations, suggesting a saturation effect where additional oxygen from methanol has a reduced influence on further lowering CO emissions, as shown in Fig. 4. This improvement in combustion efficiency contributed to lower CO emissions, consistent with similar findings by other researchers using methanol-diesel fuel mixtures (Sayin [15]).

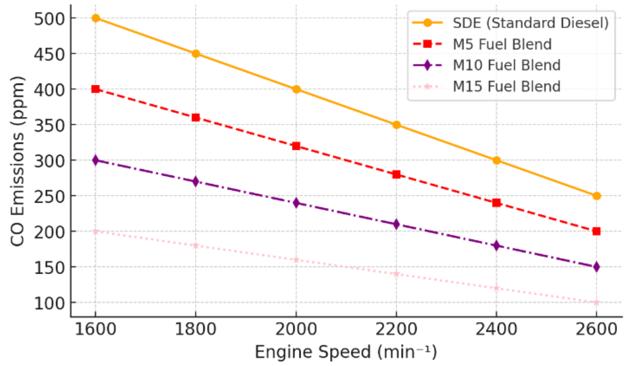

Fig. 4. The relationship between CO emissions and engine speed for different fuel blends (SDE, M5, M10, and M15)

3.6. Nitrogen oxides emissions

Nitrogen oxides, which include nitrogen dioxide (NO_2) and nitric oxide (NO), are among the most significant emissions from compression ignition engines. The formation of NO_x is highly influenced by factors such as in-cylinder temperature, oxygen content, and the residence time available for the reaction [3]. Figure 5 illustrates the variations in NO_x emissions for diesel fuel and various fuel blends at different engine speeds. The experimental results indicate that the M15 fuel blend produces the highest NO_x emissions among the blends. At 1600 min^{-1}, NO_x levels for M15 were recorded at 508 ppm, compared to 418, 395, and 385 ppm for M10, M5, and SDE, respectively. When compared to SDE, NO_x emissions increased by 38%, 8%, and 2.5% for M15, M10, and M5, respectively. A similar trend was observed in a study by Kulakoğlu [7], where an increase in methanol content also led to higher NO_x emissions.

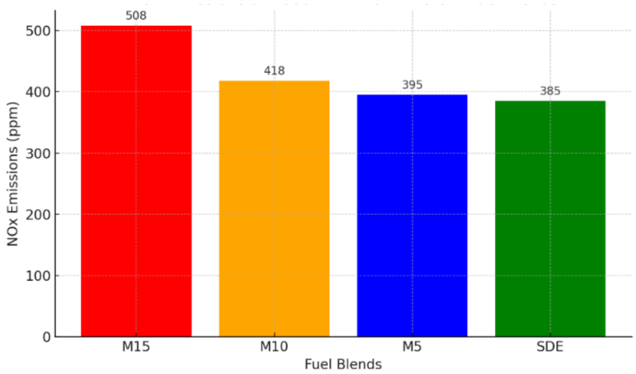

Fig. 5. The NO_x emissions for different fuel blends at 1600 min^{-1}

Generally, NO_x concentrations increased with engine speed but began to plateau after reaching the engine's maximum torque speed of 1600 min^{-1}. The higher NO_x emissions in methanol blends can be attributed to methanol's lower cetane number and higher oxygen content, which raise peak combustion temperatures. However, methanol's lower LHV and higher latent heat of vaporization, which are more than twice and four times those of diesel fuel, respectively, help mitigate this temperature rise [15]. Despite the cooling effect of methanol's high latent heat, the influence of increased oxygen content and cetane number at higher engine speeds results in a net increase in NO_x emissions, particularly for the M15 blend.

3.7. Carbon dioxide emissions

One common byproduct of combustion is carbon dioxide. Ideally, a hydrocarbon fuel should burn to produce only water (H_2O) and CO_2 [2]. Consequently, an increase in CO_2 emissions, accompanied by a decrease in hydrocarbons and carbon monoxide emissions, indicates more efficient combustion. Thus, while the trends shown in a CO_2 chart are similar to those for HC and CO emissions, it offers a distinct perspective on the combustion characteristics of a particular fuel. The chart also highlights the difference between base diesel fuel and methanol blends. Methanol tends to increase the rate of CO_2 emissions, particularly at lower engine speeds (800 to 1000 min^{-1}). However, this difference diminishes at higher engine speeds (2000 to 2700 min^{-1}) due to the reduced combustion time at these speeds.

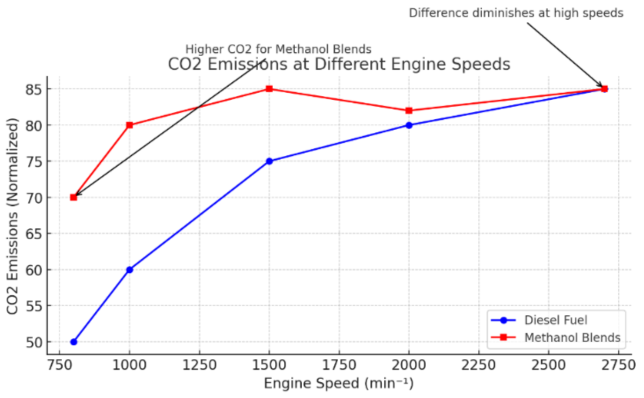

Fig. 6. Depicting CO_2 emissions for diesel fuel and methanol blends at various engine speeds

3.8. Hydrocarbon emissions

Unburned hydrocarbon emissions, also known as total hydrocarbon emissions, are primarily produced due to incomplete combustion and engine lubrication. These organic molecules in their gaseous state contribute to particulate pollution, with solid hydrocarbons forming a part of this category. In compression ignition engines, HCs are typically more prominent at low engine loads. At these low loads, fuel is less likely to impinge on surfaces, but lean fuel-air mixtures may remain and escape into the exhaust due to poor fuel distribution, excess air, and lower exhaust temperatures [4].

The addition of methanol to diesel fuel enhances combustion by increasing the oxygen available for burning. This leads to higher combustion temperatures, particularly in fuel-rich areas, which improves the overall combustion process. As a result, particulate matter in lean fuel-air mixtures, which is typically produced at low temperatures, decreases. Moreover, methanol's polar nature reduces its absorption by non-polar lubricating oils, further reducing the likelihood of UHC emissions [4]. The higher temperature in the combustion chamber facilitates easier fuel-oxygen reactions, and the increased flame speed of alcohols further accelerates the combustion process. Sayin [15] suggests that the higher combustion temperature encourages more complete combustion, reducing THC emissions.

This finding is consistent with the study's results, where engine speed also plays a significant role in the combustion process. At higher speeds, the brief combustion process leads to lower HC emissions [9]. For instance, at 1800 rpm, the HC emissions were 30 ppm, whereas at 1000 rpm with M10, the value increased to 70 ppm. Earlier studies have shown that HC emissions tend to decrease as methanol content increases [6–14].

The reduction in HC emissions with rising methanol levels can be attributed to three main factors. First, methanol molecules contain more hydrogen and less carbon than diesel molecules, with diesel molecules having 14 times more carbon and seven times less hydrogen. As the methanol content increases, the HC levels decrease due to the reduction in carbon and hydrogen in the fuel mixture. Second, the combined fuel's higher combustion temperature helps to burn lean HC-air mixtures. Lastly, methanol provides additional oxygen to fuel-rich regions in the combustion chamber, leading to enhanced combustion and a further reduction in HC emissions.

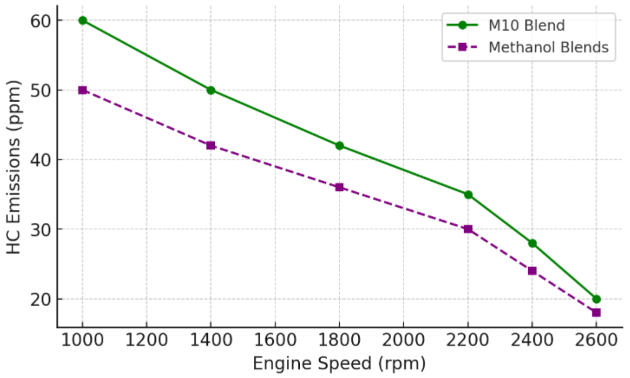

Fig. 7. UHC emissions at different engine speeds for the M10 blend and methanol blends

3.9. Particulate matter (PM) emissions

Figure 8 illustrates the variation of particulate matter emissions with engine speed in grams per kilowatt-hour (g/kWh).

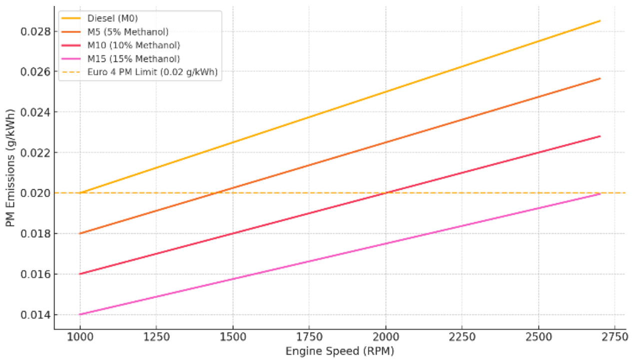

Fig. 8. PM emissions for diesel fuel and different methanol-diesel blends at various engine speeds

The results reveal a consistent increase in PM emissions with rising engine speed for all fuel types. Among these, the M0 (pure diesel) configuration shows the highest PM levels, exceeding 0.028 g/kWh at the upper speed range, and remaining above the Euro 4 PM emission limit of 0.02 g/kWh across the entire rpm spectrum. The addition of methanol leads to a progressive reduction in PM emissions. The M5 blend demonstrates moderate improvement. Notably, the M15 blend achieves the lowest PM levels.

4. Conclusions

This research investigated the feasibility of dual-fuel operation in a compression ignition engine using diesel and methanol mixtures. Experiments were conducted under steady-state conditions at ten distinct engine speed points to evaluate the effect of methanol on engine performance and exhaust pollutants. The results showed that as methanol content in the fuel blends increased, engine power declined, although this reduction became less significant at higher engine speeds. Brake thermal efficiency decreased at lower engine speeds with the inclusion of methanol, but no noticeable change occurred at mid to high engine speeds, indicating that methanol's impact on efficiency is more pronounced at lower speeds. The lower LHV of methanol was the main factor behind the increase in brake specific fuel consumption across all fuel blends, with higher methanol content leading to a greater rise in BSFC. In terms of exhaust emissions, CO and HC levels were reduced as methanol content increased, owing to the higher oxygen content of methanol, which improved combustion. However, NO_x emissions increased with the rise in methanol percentage. Overall, while methanol blending offers advantages like reduced CO and HC emissions, it also presents challenges, including engine power loss, increased fuel consumption, and elevated NO_x emissions. These findings highlight the need for careful selection of methanol content and engine operating conditions to optimize the benefits of dual-fuel systems. Further research could focus on implementing strategies to mitigate NO_x emissions while retaining the benefits of methanol-diesel blending. Additionally, further investigation into particulate emissions will be conducted using advanced particle measurement systems. This will include analysis of both particle number and size distribution under various engine operating conditions to provide a more comprehensive assessment of methanol's impact on total emission behavior in CI engines.

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