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Emission Characteristics of Oxygenated Diesel Blends Under Varying Engine Speeds

Syazwana Sapee[1], Ahmad Fitri Yusop[1], Fitri Khoerunnisa[2], Muhibbuddin[3]

[1]Faculty of Mechanical and Automotive Engineering Technology, Universiti Malaysia Pahang Al Sultan Abdullah, 26600, Malaysia
[2]Department of Chemistry, Faculty of Mathematics and Science, Indonesia University of Education, Indonesia
[3]Department of Mechanical and Industrial Engineering, Universitas Syiah Kuala, Banda Aceh, 23111, Indonesia

Corresponding Author: syazwana.sapee@gmail.com

Abstract

This study investigates the exhaust emission characteristics of various oxygenated diesel blends under different engine speeds and high engine loads. The primary emissions analysed include carbon dioxide (CO_2), carbon monoxide (CO), and nitrogen oxides (NO_x), which are key indicators of combustion quality and environmental impact. Experimental tests were performed using pure diesel and its blends with turpentine, alpha-pinene, and oxygenated additives. The results revealed that CO_2 emissions increased with engine speed for all fuels, peaking at 2,400 rpm, where the highest CO_2 level recorded was approximately 11.2% for the APD blend. Notably, the OAPD blend showed the lowest CO_2 emissions across all speeds, indicating less efficient combustion. CO emissions also rose with engine speed, reaching a maximum of 0.65% for diesel at 2,400 rpm. However, the use of oxygenated blends significantly reduced CO emissions by 0.44% for OTD and by 28.3% for both APD and OAPD, due to improved atomization and fuel-air mixing. NO_x emissions also increased with engine speed, from 86 ppm at 1,200 rpm to 238 ppm at 2,400 rpm. Blends with turpentine and alpha-pinene exhibited higher NO_x levels compared to diesel, due to greater premixed combustion and higher in-cylinder peak temperatures. Overall, the findings suggest that oxygenated additives can effectively reduce CO emissions but may increase NO_x levels, highlighting a trade-off in emission behaviours that must be considered when developing cleaner alternative fuels.

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1. Introduction

The increasing environmental concerns over greenhouse gas (GHG) emissions and air pollutants from internal combustion engines (ICEs) have prompted extensive research into alternative fuels that are more environmentally friendly. Diesel engines, widely used in transportation and industrial sectors, are known for their high thermal efficiency. However, they emit substantial quantities of harmful exhaust gases, including carbon monoxide (CO), carbon dioxide (CO_2), and nitrogen oxides (NO_x), which contribute to air pollution and global warming [1–4]. Therefore, the search for cleaner-burning fuels has become critical in mitigating the environmental impact of diesel engines. One promising approach is the use of oxygenated fuels, which involve blending diesel with renewable additives that contain inherent oxygen molecules. These oxygenated compounds, such as turpentine and alpha-pinene derived from biomass sources, have been shown to enhance combustion characteristics by promoting better fuel-air mixing and reducing particulate emissions [5–8]. The oxygen content in these additives helps promote more complete combustion, thereby reducing CO emissions and unburned hydrocarbons.

Previous studies have demonstrated that adding turpentine to diesel improves atomisation due to its lower viscosity and higher volatility compared to conventional diesel. This leads to a finer fuel spray, faster evaporation, and better premixed combustion, resulting in reduced CO and particulate emissions [9–12]. Similarly, alpha-pinene, a significant constituent of turpentine oil, has shown potential as a fuel additive due to its favourable chemical properties, which enhance ignition and combustion efficiency [13–16]. However, while oxygenated additives reduce CO and hydrocarbon emissions, they may also increase NO_x emissions. This is primarily due to elevated in-cylinder temperatures and enhanced premixed combustion that occur because of improved fuel atomization and increased oxygen availability. According to the extended Zeldovich mechanism, NO_x formation is highly dependent on combustion temperature, oxygen concentration, and residence time [17–20]. Therefore, the use of oxygenated fuels presents a trade-off between reducing incomplete combustion products and controlling thermal NO_x formation.

Additionally, the effect of engine speed on emission characteristics has been well-documented. Increasing engine speed typically results in higher fuel injection rates, shorter residence times, and increased turbulence within the combustion chamber. These conditions can either enhance or impair combustion depending on fuel properties and blend ratios. Studies have reported that higher engine speeds improve CO_2 emissions due to more complete combustion but may worsen CO and NO_x emissions due to insufficient oxygen and temperature spikes [21–24]. This study aims to evaluate the emission characteristics of diesel blended with turpentine, alpha-pinene, and oxygenated additives under varying engine speeds and high-load conditions. By analysing CO_2, CO, and NO_x emissions, this research provides insight into how these alternative fuels influence engine combustion behaviour. The findings aim to support the development of cleaner, more sustainable fuel options for compression ignition engines, while addressing the trade-offs between different types of emissions.

The specific objective of this study is to investigate the influence of turpentine- and alpha-pinene-based oxygenated additives on the emission characteristics of diesel engines, with a particular focus on variations in CO_2, CO, and NO_x emissions at different engine speeds under high-load conditions. Unlike previous studies that typically focused on single-component additives or limited speed ranges, this research presents a comparative analysis of multiple fuel blends, including OTD, APD, and OAPD, across a full range of engine speeds up to 2,400 rpm. The novelty of this study lies in its integrated approach to assessing both the positive and adverse emission impacts of using multi-component oxygenated bio-additives, thereby providing a more comprehensive understanding of combustion-emission behaviour under realistic engine operating conditions. This work offers valuable experimental data for optimising future fuel formulations that aim to balance environmental performance and engine efficiency.

2. Methodology

Exhaust emission analyser

In this study, during the experimental engine test, the exhaust gas emissions produced by the engine were recorded using a KANE AUTOplus 4-2 series exhaust gas analyser, as shown in **Figure 1**. The analyser can measure up to four gases, such as CO, CO_2, O_2, and NO_X, from exhaust gas emissions after the combustion process. The specifications of the KANE AUTOplus 4-2 series exhaust gas analyser are presented in **Table 1**. Before proceeding with the tests, the supplier calibrated the gas analyser to ensure the accuracy and precision of the exhaust gas measurements. During the experimental engine test, the engine was run for approximately 5–10 minutes before the reading was taken to ensure that it had achieved a stable condition at the required speed and load. Then, the analyser test probe was inserted into the exhaust pipeline to collect gas from the engine while it was running. The data displayed on the device was recorded. After each test, the analyser was disconnected from the exhaust manifold pipeline and exposed to fresh air to recalibrate it to zero. This is to ensure that the analyser tube is clean from previous gases before proceeding with the following data collection. The process was repeated three times to ensure the accuracy and consistency of the results. The zero calibration with fresh air was adjusted after each test. The analyser was recalibrated after each test parameter to make sure that the data collected was valid.

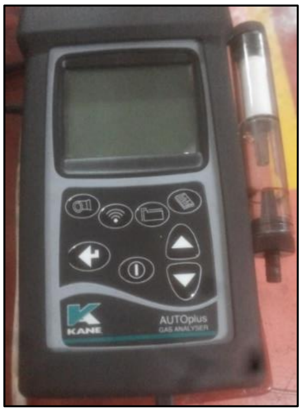

Figure 1: KANE AUTOplus 4-2 series exhaust gas analyser

Table 1: Specifications KANE AUTOplus 4-2 series exhaust gas analyser

Exhaust Gas	Measurements Range	Measurement Resolution
NO_X	0–1,500ppm	±5% or 25 ppm
CO	0–10%	±5% or 0.06%
CO_2	0–16%	±5% or 0.5%
O_2	0 ~ 21 %	±5% or 0.1%

Test fuels matrix

This study implemented the test fuel matrix shown in the. The matrix is utilised in the fuel property measurements to demonstrate the effect of different bio-additive-diesel blends on fuel properties. Furthermore, in addition to diesel as a baseline fuel, this matrix is also used for engine testing. The bio-additives, namely turpentine, alpha-pinene, oxygenated turpentine, and oxygenated alpha-pinene, were added to diesel at a volume ratio of 2%. The notation for each test fuel is also indicated in **Table 2**.

Table 2: Test fuel matrix and notation

Test Fuels	Notation
Diesel	D
Turpentine-diesel	TD
Alpha pinene-diesel	APD
Oxygenated turpentine-diesel	OTD
Oxygenated alpha-pinene-diesel	OAPD

Design of experiment test matrix of engine operating conditions

The engine experiment test matrix is presented in **Table 3** and **Table 4**. The test was carried out using five different types of test fuels, including pure diesel as the baseline. During testing, the engine was subjected to three different loads: low, medium, and high. The pre-procedure of the testing was conducted first. The engine was started in idle mode using diesel fuel for approximately 30 minutes at minimal engine speed, zero engine load, and a constant engine oil temperature of 60 °C. This ensures the engine operates at steady-state conditions. To obtain the complete load operating condition for each test fuel, the engine was set at full throttle. Each test fuel has a different full load, known as 100% load. Based on that, the low (25%), medium (50%), and high loads (75%) were calculated.

At the beginning of testing, immediately after the engine reached steady-state operating conditions at 1,200 rpm, a low load was applied by the dynamometer. Again, the engine was operated until it reached a steady state, at which point the engine oil temperature reached 60 °C. The engine's performance, combustion, and emission characteristics were recorded. The speed was then increased to a new value, and data such as torque, fuel flow, air intake flow, engine oil temperature, relative humidity, ambient temperature, and ICP were measured and recorded in real-time. The engine speed was increased to 1,400 rpm, and the engine was operated until it reached a steady state. Data were collected again. The engine testing was continued with an additional engine speed at 200-rpm intervals from the minimum engine speed of 1,200 rpm to the maximum engine speed of 2,400 rpm. The speed of each engine's data was collected. After that, the engine load was increased to a medium load, with engine speeds ranging from 1,200 rpm to 2,400 rpm. Then, the engine load was increased to a high load, with engine speeds ranging from 1,200 rpm to 2,400 rpm. These procedures were repeated three times.

Table 3: Design of experiment test matrix for fuel testing at increasing engine speed with high load

Test Fuels	Type of fuel	Type of Engine	Engine Load High (75%)	Engine Speed (rpm)	Test Number	Repeatability
			✓	1,200	1	3
D	Pure diesel		✓	1,400	2	3
TD	0.2% turpentine + 99.8% pure diesel		✓	1,600	3	3
OTD	0.2% oxygenated turpentine + 99.8% pure diesel	Yanmar Single Cylinder Diesel Engine TF120M	✓	1,800	4	3
APD	0.2% alpha pinene + 99.8% pure diesel		✓	2,000	5	3
OAPD	0.2% oxygenated alpha pinene + 99.8% pure diesel		✓	2,200	6	3
			✓	2,400	7	3

Table 4: Design of experiment test matrix for fuel testing at increasing load with 1,800 rpm

Test Fuels	Type of fuel	Type of Engine	Engine Speed (rpm)	Engine Load			Test Number	Repeatability
				Low (25%)	Medium (50%)	High (75%)		
D	Pure diesel	Yanmar Single Cylinder Diesel Engine TF120M	1,800	✓	✓	✓	1	3
TD	0.2% turpentine + 99.8% pure diesel			✓	✓	✓	2	3
OTD	0.2% oxygenated turpentine + 99.8% pure diesel			✓	✓	✓	3	3
APD	0.2% alpha pinene + 99.8% pure diesel			✓	✓	✓	4	3

Test Fuels	Type of fuel	Type of Engine	Engine Speed (rpm)	Engine Load			Test Number	Repeatability
				Low (25%)	Medium (50%)	High (75%)		
OAPD	0.2% oxygenated alpha pinene + 99.8% pure diesel			✓	✓	✓	5	3

The engine operates on diesel fuel at the start of each test before switching to other tested fuels. This is to ensure that the residue of previous fuel has been flushed. The engine fuel tests were repeated three times for each fuel under the specified operating conditions to provide accurate and reliable measurements and data accuracy. The data were then analysed and compared with diesel fuel as a baseline and related literature. After the recorded data were deemed satisfactory, the subsequent fuel was tested. However, suspicious data would require repeating the testing at those engine operating conditions. These were monitored by performance criteria set, which included dynamometer operating, exhaust gas temperature readings, and emissions data as references. The experiment was stopped several times due to high EGT and high exhaust emissions compared to the reference data acquired. The experiment was continued when the engine temperature had cooled down.

3. Result & Discussion

Emission analysis of engine testing

Characteristics that are important in engine testing, aside from performance and combustion, include the engine's exhaust emissions. In this section, three major types of emissions are presented and discussed. The emissions include carbon dioxide, carbon monoxide, and nitrogen oxides.

Carbon dioxide emissions

In an ideal scenario, HC fuel combustion should produce only carbon dioxide (CO_2) and water [25]. Carbon dioxide is one of the products of C-based fuel combustion. The amount of CO_2 emitted by a diesel engine is a measure of how well the fuel is burned inside the combustion chamber. Due to the higher O_2 concentration in the combustion chamber during combustion, the majority of C will be transformed (oxidised) into CO_2. Although CO_2 is a non-toxic gas that is not classed as an engine pollutant, it is one of the components that contributes to global warming by promoting thermal radiation. Thermal radiation will be stored within the Earth's atmosphere, causing the Earth's temperature to rise [26]. The "greenhouse effect" is a well-known phenomenon that eventually leads to "global warming" of the world [27]. Many studies have suggested that CO_2 emissions released into the atmosphere by biofuel combustion may be offset by plant photosynthesis, or that the carbon cycle could be completed [28]. As a result, biofuel is a highly efficient alternative fuel for decreasing greenhouse gas emissions and addressing global warming issues. As CO_2 has a high heat capacity, it acts as a heat-absorbing agent during combustion, thereby lowering the peak temperature of the combustion chamber [29]. Furthermore, the C-H_2 ratio in fuel has an impact on CO_2 generation. When using biofuel, the amount of O_2 in the air plays a vital role in optimising engine combustion, which increases CO_2 levels [30].
Figure 2 shows the variations in CO_2 emissions for the test fuels at different engine speeds. Notably, the results show that CO2 emissions increased as engine speed increased for all test fuels. The chart shows that maximum CO_2 emissions for all test fuels occurred at the highest engine speed and decreased as the engine speed dropped. The increase in fuel consumption that occurs as engine speed rises to maintain a high engine load is a significant contributor to CO2 emissions at high engine speeds. Furthermore, the ideal combustion conditions at this stage explain the high CO_2 and low CO emissions at high engine speeds, which may be because complete combustion is more achievable. This is due to improved fuel-air mixing and higher in-cylinder temperatures and pressures at higher engine speeds. This indicates that a significant amount of carbon in fuels is converted to CO2 due to carbon combustion

with O_2 in the combustion air. The most important feature is the lack of oxygen (O2), which prevents CO from the exhaust from being converted into CO_2 [31].

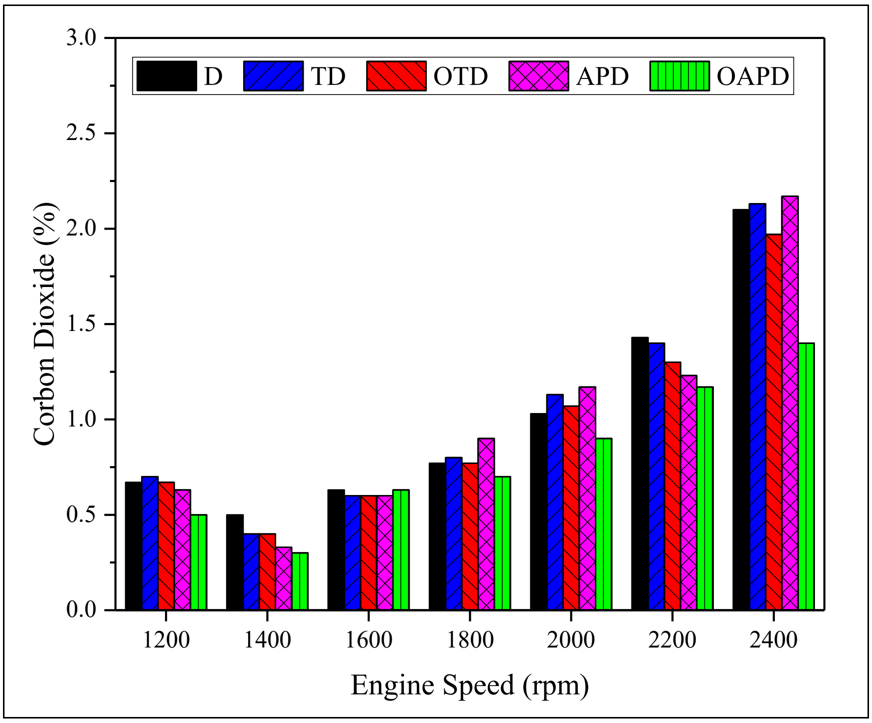

Figure 2: Effect of engine speed on the CO_2 emission of test fuels at high engine load

The engine operating under various fuel blends showed the most significant changes in CO_2 concentration levels. When compared to other test fuels, OAPD emits less CO_2. The decrease in CO_2 emissions when utilising OAPD indicates that the combustion is inefficient. It was also discovered that using TD and APD resulted in increased CO_2 emissions. It was observed that the trend of CO_2 generation was slightly higher than that of diesel fuel, which contributed to a faster mixing rate and better oxidation of fuel particles and slightly assisted the incomplete oxidation of CO to CO_2.

Carbon monoxide emissions

Carbon monoxide (CO) is a poisonous gas produced during the burning of HCs. It also represents the unused chemical energy in an internal combustion engine (ICE). As the HC fuel burns, much of the CO produced oxidises to CO_2. The air-fuel ratio (either low or rich) and the fuel's ability to achieve complete combustion through the fuel-burning stages have the most significant impact on CO emissions in ICEs [32]. As a result, it is influenced by the fuel's physical and chemical properties.

Furthermore, CO emission is influenced by the fuel's combustion efficiency, as well as the C and O_2 concentrations. The C in the fuel undergoes a series of oxidation and reduction reactions during combustion. If the combustion is complete, the carbon content of the fuel oxidises with oxygen in the air, resulting in CO and subsequently CO_2. On the other hand, if there is a lack of O_2, incomplete combustion of the fuel occurs, resulting in the formation of CO [33]. Furthermore, engine load, engine speed, combustion chamber design, over-mixing/under-mixing of fuel (air-fuel ratio), insufficient O_2, non-homogeneous blends, low reaction temperature, slow rate of oxidation, fuel properties, spray characteristics, atomisation rate, and lack of burning time for conversion can all contribute to CO formation [34].

Figure 3 illustrates the variations in CO emissions between test fuels at different engine speeds. It should be noticed that as the engine speed increased, so did CO emissions. The relationship between the increase in CO emissions and the increased engine speed in natural aspiration diesel engines is due to the increased amount of fuel injected at higher engine speeds, which allows for a higher fuel volume to be dispersed more accurately in the engine cylinder space. The reason for an increase in CO emissions with increased engine speed is due to the fuel-rich mix in the sprayed fuel jet (less O_2 available for combustion), which results in incomplete combustion of fuel and higher CO emissions. Furthermore, as more fuel is injected at higher engine speed, more C content from the fuel is available in the combustion process, which eventually increases CO emissions.

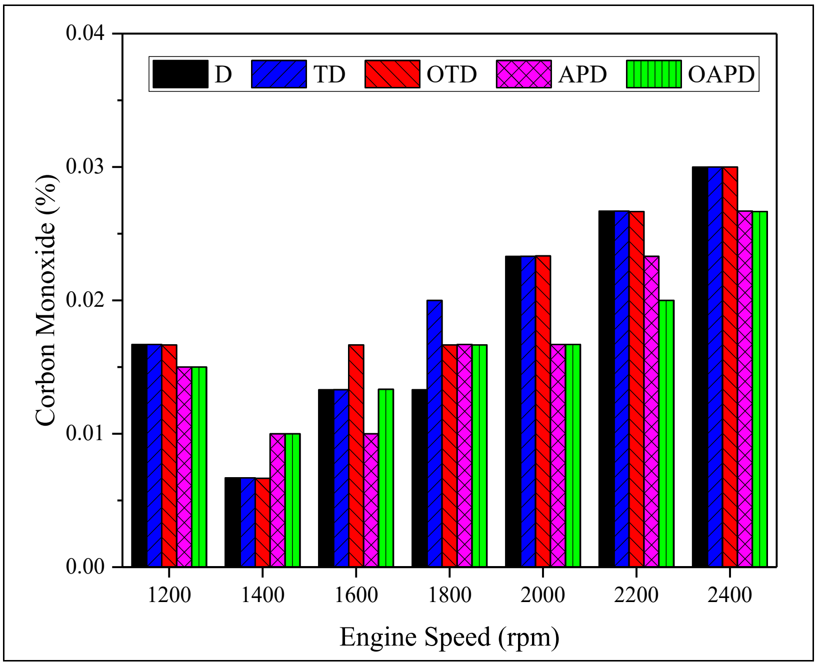

Figure 3: Effect of engine speed on the CO emission of test fuels at high engine load

Carbon monoxide emissions decreased when oxygenated additives were added to the diesel blends. When compared to diesel fuel, the additive-diesel blends produced lower CO emissions. At most engine speeds, diesel fuel emitted the highest CO emissions when compared to other test fuels. Furthermore, the reductions in CO emissions are 0.44%, 28.3%, and 28.3% for OTD, APD, and OAPD, respectively. The reason for this is that turpentine has a lower viscosity, which can lead to lighter fuel droplets, resulting in better fuel atomization and the ability to form a more homogeneous mixture of fuel and air (locally rich mixtures) in the engine cylinder, leading to significantly reduced CO emissions during combustion [5].

Furthermore, as turpentine has a higher calorific value than diesel, it requires less fuel injection at the same engine speed. Turpentine and oxygenated additives contain a higher carbon content than diesel; therefore, the combined effect of the previously mentioned variables (low viscosity, high calorific value, and high volatility) is more dominant, resulting in lower incomplete combustion of additive-diesel fuels and lower CO emissions. Additionally, conditions that lead to degradation in the combustion rate, such as the high latent temperature of vaporisation of turpentine, can cause a high oxidation reaction rate of CO, resulting in increased combustion temperature and burning speed, as well as lower CO production [35].

Nitrogen oxide emissions

The generation of NO_X emissions occurs during the combustion of the air-fuel mixture in the combustion chamber, where nitrogen (N_2) and oxygen (O2) react at high temperatures of approximately 1,800 °K [34]. Nitric oxide emissions account for many NO_X emissions, while nitrogen dioxides account for only a small percentage of NO_X emissions. Other N_2-O_2 combinations account for the rest of the NO_X emissions. Furthermore, NO_X emissions are influenced by pressure, air-fuel ratio, and combustion time [36]. Additionally, fuel properties such as bulk modulus and viscosity affect the generation of NO_X emissions [37]. The development of NO_X emissions is dependent on very high in-cylinder combustion temperatures, high O2 concentrations, prolonged residence times for reactions to occur, and the impact of the combustion zone, according to the extended Zeldovich mechanism [38].

The majority of NO_X emissions are produced during combustion, both at the flame front and the post-flame [39]. Humidity also has a significant impact on NO_X emissions. NO_X emissions are reduced as air humidity increases [40]. As a result, during all engine tests, the humidity levels were measured to perform humidity adjustment. Based on the humidity measurement findings, the NO_X was calculated as specified in the SAE Handbook [41].

Figure 4 shows a comparison of NO_X emissions for the tested fuels at various engine speeds. NOX emissions increased with engine speed for all test fuels, reaching their maximum values at the highest engine speed. In addition, the amount of NO_X emission is the lowest (86–102 ppm) at an engine speed of 1,200 rpm and increases (171–238 ppm) at an engine speed of 2,400 rpm. The reason for the rise in NOX emissions with engine speed is due to an increase in ICP and the corresponding in-cylinder combustion temperature for all test fuels, which improves thermal NO_X production and provides the necessary source of nitric oxides in compression ignition engines [42]. The fuel-to-air ratio becomes extremely high at high engine speeds, and oxygen becomes abundant. As a result, N_2 oxidation increased, along with NO_X emissions. Other studies employing turpentine-based oil observed an increase in NO_X emissions as engine speed increased [43,44]. As the engine speed increases, the temperature in the combustion chamber rises, leading to an increase in NOx emissions.

The addition of turpentine and alpha-pinene oil to diesel blends increases NOX emissions by promoting premixed combustion, which occurs due to faster burning. All the fuel blends emitted higher NO_X emissions than diesel fuel due to turpentine's higher calorific value and lower viscosity, which resulted in more premixed combustion and higher peak ICP and temperature, as well as higher NO_X emissions. As turpentine has a lower viscosity than diesel, it has better atomisation, more air entrainment, and higher fuel-air mixing rates, resulting in increased heat release during the premixed combustion phase. This results in a higher premixed combustion rate, higher peak ICPs, and higher temperatures, all of which contribute to increased NO_X emissions [32].

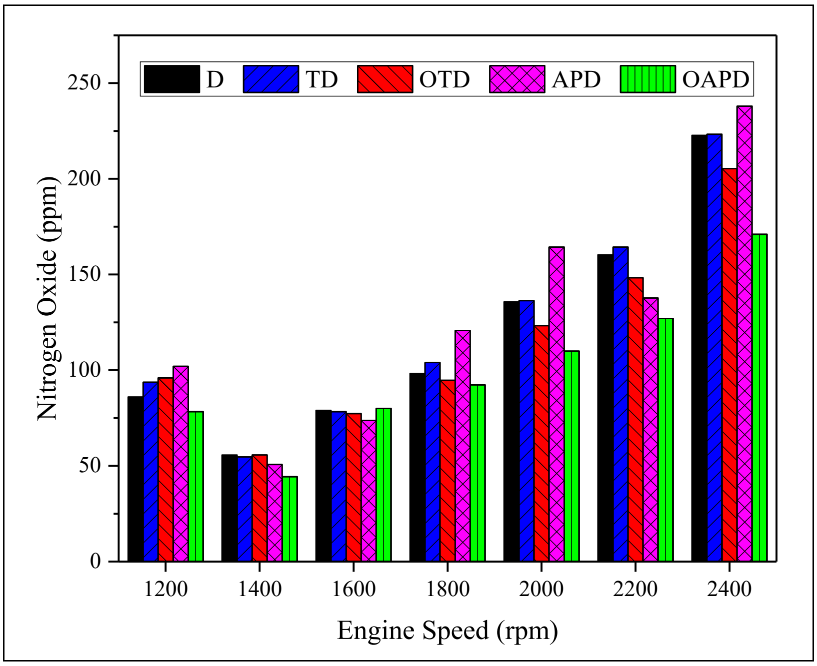

Figure 4: Effect of speed on the NO_X emission of test fuels at high engine load

4. Conclusion

This study evaluated the emission performance of various diesel fuel blends containing turpentine, alpha-pinene, and oxygenated additives under different engine speeds and high-load conditions. The experimental results demonstrate that engine speed has a significant impact on emission characteristics,

particularly CO_2, CO, and NO_x emissions. CO_2 emissions increased with engine speed across all fuel types, reaching a peak of approximately 11.2% at 2,400 rpm for the APD blend. However, the OAPD blend recorded the lowest CO_2 emissions at each engine speed, indicating less complete combustion compared to other fuels. Carbon monoxide (CO) emissions also rose with engine speed, with diesel fuel emitting the highest CO levels, peaking at 0.65% at 2,400 rpm.
In contrast, the addition of oxygenated compounds significantly reduced CO emissions by 0.44% for OTD, and by 28.3% for both APD and OAPD due to better atomisation and improved combustion efficiency. Nitrogen oxide (NO_x) emissions increased from 86–102 ppm at 1,200 rpm to 171–238 ppm at 2,400 rpm for all test fuels. Blends containing turpentine and alpha-pinene exhibited higher NO_x emissions compared to diesel, attributed to enhanced premixed combustion, higher in-cylinder peak temperatures, and improved air-fuel mixing. In summary, while oxygenated additives such as turpentine and alpha-pinene effectively reduce CO emissions, they tend to increase NO_x formation. Therefore, optimising oxygenated fuel formulations requires a balance between reducing toxic emissions and controlling thermal NO_x production to ensure cleaner and more efficient engine performance.

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