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Performance Analysis of Diesel Blends with Additives: Impact on Power, Efficiency, and Emissions

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Abstract
This study investigates the performance characteristics of an engine operating with diesel fuel blended with various additives, including turpentine oil, alpha-pinene oil, and oxygenated fuels. Engine performance was evaluated under high-load conditions at different engine speeds, focusing on brake power (BP), brake torque (BT), brake thermal efficiency (BTE), brake-specific fuel consumption (BSFC), and exhaust gas temperature (EGT). The results indicate that additive-diesel blends generally enhance engine performance compared to conventional diesel fuel. Specifically, at 1,800 rpm, alpha-pinene diesel (APD) achieved the highest BP improvement (7.33%) over diesel, while turpentine diesel (TD) recorded the highest BTE (24%) with a notable reduction in BSFC. The oxygenated additive-diesel blends further improved combustion efficiency, resulting in lower BSFC and EGT values. However, the torque performance varied, with some oxygenated additives showing a slight reduction due to increased oxygen content. The findings suggest that incorporating specific chemical additives can enhance engine efficiency and reduce fuel consumption while lowering exhaust emissions. These results support the potential of alternative fuel formulations in improving engine sustainability and performance.

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1. Introduction

The growing demand for energy and the environmental impact of fossil fuels have driven the exploration of alternative fuels that enhance engine performance while reducing emissions. Diesel engines, widely used in transportation and industrial applications, require fuel modifications to improve efficiency and sustainability. Recent studies have focused on incorporating bio-based additives into diesel to enhance combustion characteristics. Turpentine oil and alpha-pinene oil, derived from pine trees, have been identified as promising bio-additives due to their high oxygen content, improved combustion efficiency, and potential to reduce harmful emissions [1–4]. These natural additives possess higher calorific values than conventional diesel, making them suitable candidates for improving engine performance.

Brake power (BP) and brake torque (BT) are critical parameters in evaluating the effectiveness of fuel additives. Previous research has shown that including oxygenated compounds in fuel blends can enhance power output by facilitating more complete combustion [5–8]. In this study, alpha-pinene diesel (APD) achieved the highest BP improvement of 7.33% at 1,800 rpm, confirming findings that bio-additive inclusion increases power output [9–12]. However, studies also indicate that oxygenated additives may reduce torque due to changes in combustion pressure and fuel properties [13–16]. This research supports these findings by demonstrating a slight reduction in BT for oxygenated additive-diesel blends compared to non-oxygenated blends.

Brake thermal efficiency (BTE) is another crucial factor in determining fuel performance. According to previous studies, adding oxygenated compounds enhances fuel-air mixing, improving thermal efficiency [17–20]. This study found that turpentine diesel (TD) achieved the highest BTE of 24% at 1,800 rpm, outperforming baseline diesel (22.19%). These results align with findings that pine-based additives significantly increase BTE [21–23]. Additionally, oxygenated additive-diesel blends such as oxygenated alpha-pinene diesel (OAPD) demonstrated an improvement in BTE (23.79%), reinforcing prior conclusions that increased oxygen content in fuels leads to more efficient combustion [24–27].

Brake-specific fuel consumption (BSFC) is a key parameter influencing fuel economy. Studies have shown that fuel blends with higher calorific values generally exhibit lower BSFC, reducing overall fuel consumption [28–31]. The present study supports these observations, showing that APD achieved a 10.43% reduction in BSFC at 1,200 rpm, while TD improved BSFC by 8.00% at 1,800 rpm. These results align with prior research indicating that turpentine-based fuels lower BSFC due to their enhanced combustion characteristics and higher heating values [32–36]. Furthermore, this study confirms the findings of Khan et al. (2022), who reported that oxygenated additives enhance BSFC by ensuring more complete combustion.

Exhaust gas temperature (EGT) serves as an indicator of combustion efficiency and emission characteristics. Studies have suggested that oxygenated additives can reduce EGT by facilitating cleaner combustion and reducing heat loss (Bhaskar et al., 2013). This study found that OAPD achieved a 20.06% reduction in EGT at 2,400 rpm, confirming observations that oxygenated fuels exhibit lower EGT due to better atomization and enhanced oxidation [37–39]. Furthermore, Similar results were reported, indicating that lower viscosity and volatility in additive-diesel blends contribute to improved spray characteristics, reducing EGT level [40–42].

This study contributes to the growing research on alternative diesel fuel formulations. Integrating findings from previous studies highlights the potential benefits of using turpentine oil and alpha-pinene oil as diesel additives. The improvements observed in BP, BTE, and BSFC, along with reductions in BSFC and EGT, demonstrate that these bio-additives can enhance engine efficiency while minimising environmental impact. These results support further exploration of bio-based fuel additives as viable alternatives to conventional diesel fuels in pursuit of more sustainable and efficient combustion technologies.

2. Experimental engine test setup

This section describes the methods used to study the performance, combustion, and exhaust emissions of test fuels in a diesel engine. This section outlines the experimental engine test setup, including engine specifications, installed systems with necessary equipment, measurement techniques, and the instruments used for data collection. There is also a comprehensive overview of the sensor integration and data acquisition system. This section covers the schematic diagram of the experimental engine setup, engine specifications, components, and measurement methods. The engine test rig was set up, as presented in the schematic diagram in **Figure 1**. The experiment was conducted at the Engine Performance Laboratory, Faculty of Mechanical and Automotive Engineering Technology, Universiti Malaysia Pahang, Pekan, Pahang.

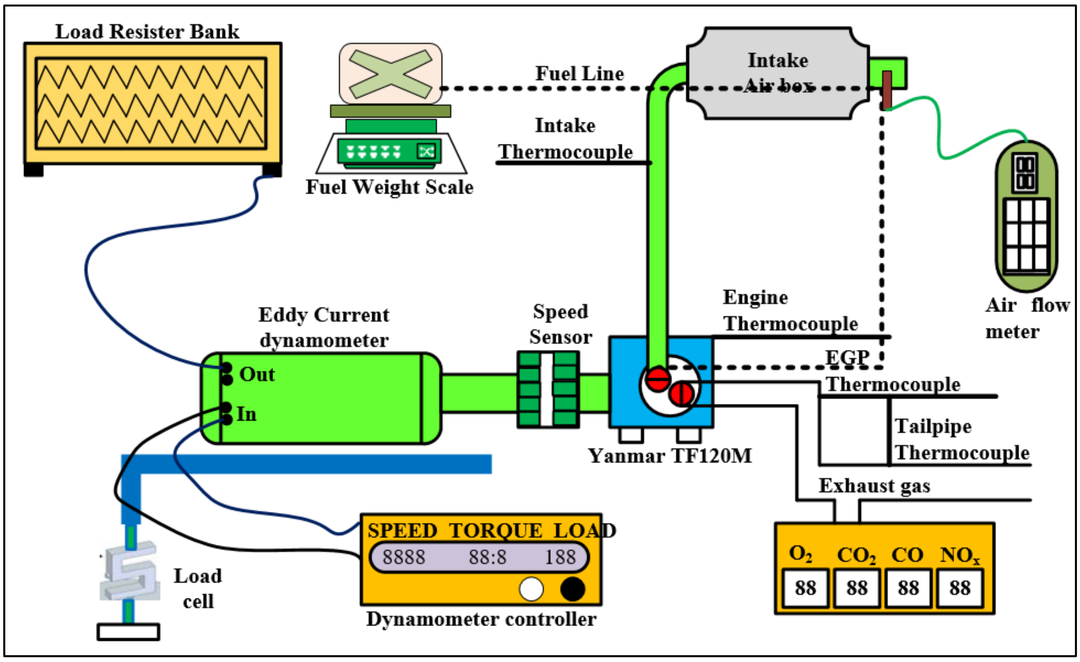

Figure 1: Diagrammatic representation of the diesel engine test setup

Table 1: Specification of Yanmar TF120M diesel engine

Description	Specification
Engine model	YANMAR TF120M
Engine year	2016
Engine type	Horizontal, four-cycle, four-stroke, diesel engine
Number of cylinders	1
Continuous power output (kW)	7.82 kW at 2,400 rpm
Rated power output (kW)	8.94 kW at 2,400 rpm
Bore × Stroke (mm)	92 × 96
Displacement (L)	0.638
Maximum torque (kgf · m/rpm)	43.35 N · m / 1,800 rpm
At 1-hr. rated output (hp/rpm, kW)	12.0 hp / 2,400 rpm (9.0 kW)
Rated continuous output (hp/rpm, kW)	10.5 hp / 2,400 rpm (7.8 kW)
Specific fuel consumption (gr/hp.h)	169 gr/hp.h
Injection timing	17°bTDC
Compression ratio	17.7
Combustion system	Direct injection
Aspiration	Natural aspiration
Cooling system	Water-cooled
Starting system	Manual (hand) starting.
Position of PTO	Flywheel side
Direction of crankshaft rotation	Counterclockwise viewed from the flywheel.

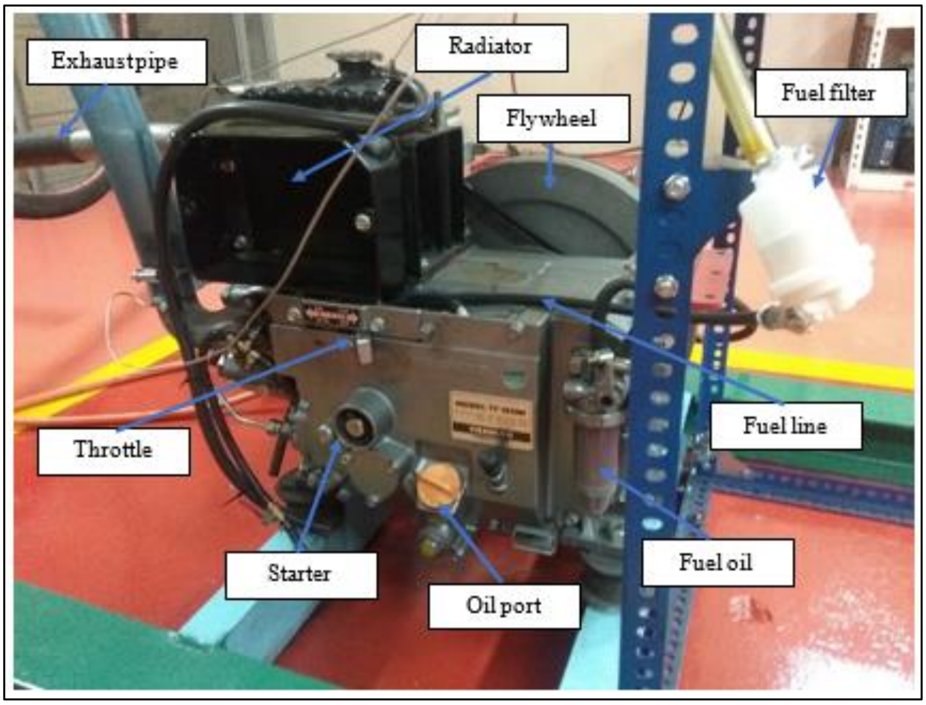

Figure 2: Yanmar TF120M engine parts

The main component of this experiment is the engine. The engine used is a single-cylinder, four-stroke, naturally aspirated, water-cooled diesel engine, specifically the direct-injection CI Yanmar TF120M engine. **Figure 2** shows the engine, highlighting its key components, design features, and overall structure, which are essential for understanding its operational characteristics and performance analysis. **Table 1** presents detailed specifications of the Yanmar TF120M engine. The engine used is unmodified with a 17.7 compression ratio. This engine is equipped with an exhaust gas recirculation (EGR) system. However, in this study, the EGR mode is set to off.

3. Result & Discussion

Performance analysis of engine testing

This subchapter presents the performance analysis of engine testing for each test fuel. Three different engine loads and seven different engine speeds were used to test the performance. All the results obtained using each blended fuel are compared to the baseline fuel, diesel. The engine performance characteristics presented and discussed include brake power (BP), brake torque (BT), brake thermal efficiency (BTE), and brake-specific fuel consumption (BSFC). To simulate the effect of engine load, the engine speed was set to a constant speed of 1,800 rpm. This is because, as shown in **Error! Reference source not found.** The intersection between the optimal power and torque of the engine occurred at this engine speed. In contrast, the engine load was maintained at a high level to demonstrate the effect of engine speed.

Brake power

The present study determined the engine's BP output using a hydraulic dynamometer connected to a shaft. Despite having a lower cetane number than diesel fuel, turpentine oil, alpha pinene oil, and oxygenated fuels have higher O_2 content, latent heat of evaporation, and higher calorific value than diesel fuel [43,44]. As a result, adding these additives to blended fuels modifies engine performance and power output. The graph in **Figure 3** indicates the power output of blended fuels at high load.

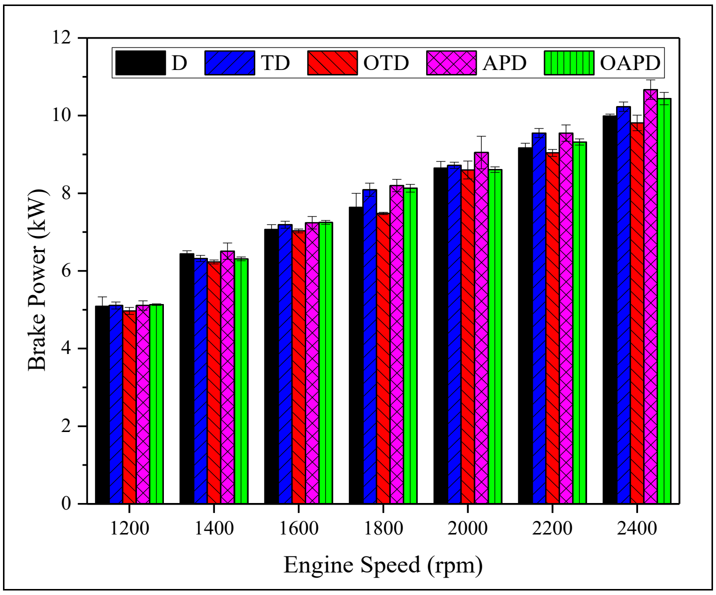

Figure 3: Effect of engine speed on the engine BP of test fuels at high load

Figure 3 presents the effect of engine speed on the engine BP of test fuels at high load. All the tested fuels showed a linear increase in BP as the engine speed increased. Generally, the BP supplied by all blended fuels is slightly lower than that of the baseline D at lower speeds. For instance, at 1,400 rpm, the BP of test fuels is 6.44 kW, 6.32 kW, 6.23 kW, 6.51 kW, and 6.31 kW for D, TD, OTD, APD, and OAPD, respectively. Hence, the declines are 1.86% (TD), 3.31% (OTD), -1.04% (APD), and 2.07% (OAPD). However, the BP of additive-diesel blends is higher than D at higher engine speeds. It can be observed that at 2,400 rpm, the BP of D, TD, OTD, APD, and OAPD is 9.99 kW, 10.23 kW, 9.81 kW, 10.67 kW, and 10.44 kW, respectively. The improvement at 2,400 rpm for TD, OTD, APD, and OAPD is 2.40%, 1.74%, 6.81%, and 4.54%, respectively. Overall, at high load, the most considerable improvement of BP at 1,800 rpm was achieved by APD, with a 7.33% increase compared to baseline D. This is due to the calorific value of alpha-pinene oil. In general, TD and APD produced more engine power than diesel fuel. This is because turpentine and alpha-pinene oil have higher calorific values than diesel. According to a prior study, the calorific values of turpentine and alpha-pinene oil are approximately 3–5.4% higher than those of D [43,44]. This finding is consistent with prior research, which found that adding alpha-pinene oil to the combustion mixture enhanced the power output [45]. Moreover, the power output of oxygenated additive-diesel fuels increased by adding more O_2 to the combined fuels [46]. The higher powers generated by the additive-diesel blend may be responsible for the superior oxygen content inside the additive. The higher O_2 content in the additive may be accountable for the higher power generated by the additive-diesel blends. In short, the high O_2 content used in fuel-rich areas leads to good atomisation, low viscosity, higher combustion efficiency, and more power generation [47].

Brake torque

Figure 4 presents the effect of engine speed on the engine BT of test fuels at high load. The figure shows that the engine torque increased as the engine speed increased to a maximum value of 1,800 rpm, after which it started to drop due to friction losses. There is a potential that the combustion chamber may not be able to absorb a complete charge of air at high speed [48]. The BT of additive-diesel blend fuels improved for most engine speeds. Adding additives to diesel-blended fuels enhanced the heating values of the blended fuels and improved the ID during combustion. As a result, the BT of blended fuels is higher than that of D [49]. For instance, at 1,800 rpm with high load, the BT for D, TD, OTD, APD, and OAPD is 24.32 Nm, 25.76 Nm, 23.81 Nm, 26.10 Nm, and 25.89 Nm, respectively. The percentage improvements of BT for test fuels with additives of TD, OTD, APD, and OAPD are 5.93%, -2.09%, 7.33%, and 6.46%, respectively. It is also worth noting that there are differences in BT between blended fuels with additives and oxygenated additives, as illustrated in the figure. For all engine speeds, it was evident that oxygenated additives give lower BT values than the additives before oxidation. At 1,800 rpm, the values of BT for TD and OTD dropped from 25.76 Nm to 23.81 Nm. This is similar to APD and OAPD, where the BT values decreased from 26.10 Nm to 25.89 Nm. This is due to the additional force the oxygenated additives apply to the piston's tip. When fuel is pumped into the combustion chamber, it creates a higher pressure against the piston, reducing the torque [48].

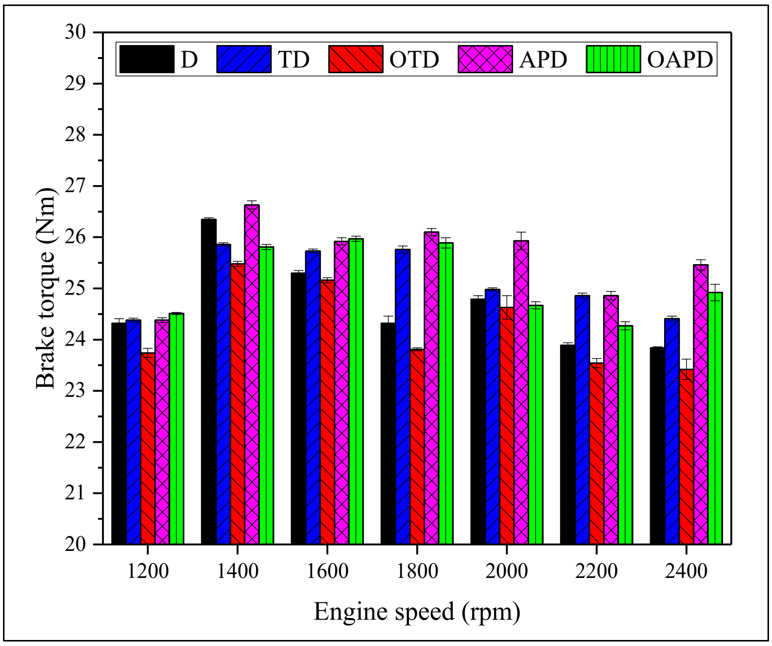

Figure 4: Effect of engine speed on the engine BT of test fuels at high load

Brake thermal efficiency

The percentage of work done by an engine shaft divided by the energy input is known as BTE. The efficiency with which an engine transforms heat from chemical energy stored in the fuel to mechanical energy (shaft work) is practical [50]. The BTE is calculated using the fuel's measured energy content (calorific value) and engine BP. A higher BTE is preferred, as it implies that the engine performs more efficiently with complete fuel combustion [51]. **Figure 5** shows the effect of engine speed on the engine BTE of test fuels at high load. The test findings show that the BTE of all test fuels improved as the engine speed increased to 1,800 rpm. TD and APD have the highest (20.26–24%) and lowest (17.82–20.62%) BTE values, respectively, at all engine speeds. At 1,800 rpm, the BTE of TD is 24%, which is higher than the baseline D (22.19%). At the same engine speed, the BTE of OAPD improved to 23.79%. However, the BTE of APD and OTD decreased to 20.62% and 20.4%.%, respectively. This difference can be attributed to the higher O2 concentration in blended fuels compared to mineral diesel, which enhances fuel combustion and improves fuel lubricity. These findings are supported by a prior study [52], which found that increasing the turpentine concentration in the diesel blend increased the BTE. Moreover, from the figure, it is notable that the BTE dropped as the engine speed increased from 1,800 rpm onwards. Due to insufficient air, the BTE decreased for all fuels when the engine speed increased from 1,800 rpm to 2,400 rpm, resulting in partial fuel combustion [53]. The figure demonstrates that at most engine speeds, the BTE of TD and OAPD increased compared to D. These findings are consistent with a recent study, which found that adding pine additives to diesel-blended fuels improved the BTE [54].

Additionally, the spray quality is enhanced because chemical additives have lower boiling points, densities, and viscosities than diesel. Furthermore, as the additive's O_2 ratio increases, heat losses in the cylinder reduce, resulting in improved BTE. The increase in BTE in the presence of chemical additives is likely due to increased reaction activity as the additive fraction in the blended fuel increases, resulting in a shorter combustion duration (CD) [55].

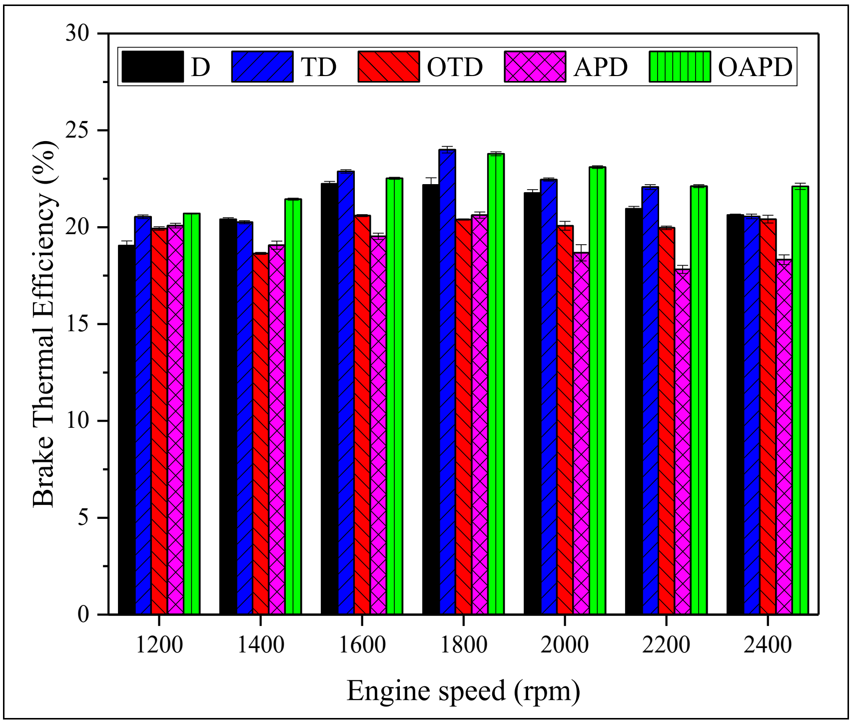

Figure 5: Effect of engine speed on the engine BTE of test fuels at high load

Brake-specific fuel consumption

During engine testing, the fuel flow rate is recorded. Then, the fuel consumption is calculated based on the flow rate of fuel per unit of time. It can also be understood in terms of the weight of fuels (in units of grams) consumed during combustion to produce 1 kW of BP in a given amount of time (in units of hours). The relationship between the total fuel consumption and the power generated by the engine, as well as the viscosity, density, and calorific value of the fuel utilised, is known as BSFC.

Figure 6 shows the effect of engine speed on the engine BSFC of test fuels at high load. At low engine speeds (1,200–1,800 rpm), all tested fuels showed a declining trend of BSFC. Afterwards, the BSFC increased gradually from 1,800 rpm to 2,400 rpm. The initial engine speed requires more fuel to overcome mechanical friction; therefore, the BSFC is higher if the engine speed is not optimal, higher or lower than the economical speed [56]. Increased BSFC is achieved by partially burning fuel with lower energy content and higher viscosity [57]. Overall, the test fuels with additives have lower BSFC than diesel; hence, the enhancement of BSFC by additives is quite significant. This is because turpentine and alpha-pinene have higher heating values than diesel, and these additive-diesel blends exhibit lower fuel consumption compared to pure diesel [58]. The finding aligns with studies that have observed a reduced BSFC when applying turpentine to the fuel [59,60]. For example, at 1,200 rpm, the BSFC of D, TD, OTD, APD, and OAPD is 200.41 g/kWh, 185.02 g/kWh, 180.84 g/kWh, 179.51 g/kWh, and 190.39 g/kWh, respectively. Hence, the enhancement of additive-diesel blends' BSFC is 7.68%, 9.76%, 10.43%, and 5.00% better than diesel for TD, OTD, APD, and OAPD, respectively. At 1,800 rpm, the BSFC of D, TD, OTD, APD, and OAPD is 172.08 g/kWh, 158.31 g/kWh, 176.74 g/kWh, 174.79 g/kWh, and 165.73 g/kWh, respectively, with percentage differences concerning diesel of 8.00%, -2.71%, -1.58%, and 3.69% for TD, OTD, APD, and OAPD, respectively. On the other hand, at 2,400 rpm, the BSFC of D, TD, OTD, APD, and OAPD is 185.07 g/kWh, 184.84 g/kWh, 176.57 g/kWh, 196.74 g/kWh, and 178.34 g/kWh, respectively. The enhancement by TD, OTD, APD, and OAPD is 0.13%, 4.60%, -6.30%, and 3.64%, respectively, compared to the baseline diesel. APD can see the highest enhancement of BSFC at 1,200 rpm with a 10.43% improvement compared to diesel. At all engine speeds, oxygenated additive-diesel blends, especially by OAPD, produced lower BSFC than additives not oxidised. For instance, at 2,400 rpm, the BSFC for TD and OTD dropped from 184.84 g/kWh to 176.57 g/kWh. It is identical to APD and OAPD, where the BSFC decreased from 196.74 g/kWh to 178.34 g/kWh. Increased O_2 content in oxygenated additives blended fuels enhanced the

BSFC. This is because additive-diesel fuel with a higher O_2 concentration than diesel ensures complete combustion [61].

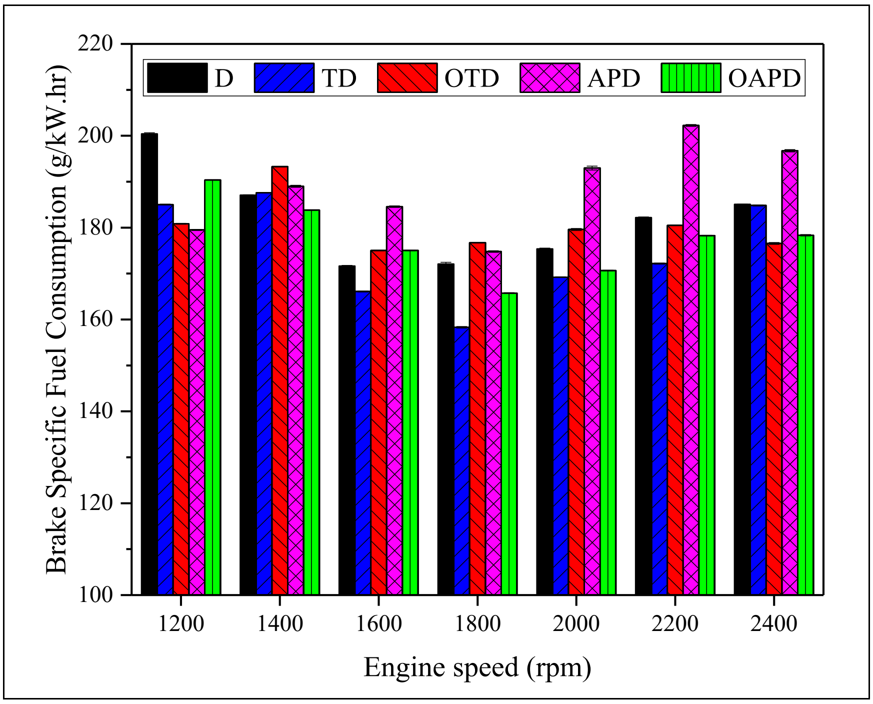

Figure 6: Effect of engine speed on the engine BSFC of test fuels at high load

Exhaust gas temperature

Exhaust gas temperature (EGT) is a key indicator of the heat emitted by the tested fuel during combustion, and it is also used in determining exhaust emission levels. **Figure 7** shows the differences in the EGT for all test fuels under various engine speed conditions at high loads. For all the additive-diesel blends, the EGT increased continually as the engine speed increased. In addition, the mean temperature increased linearly from 304.5 °C at the lowest engine speed to 449.4 °C at the highest. This rise in EGT with engine speed is because more fuel must be consumed to generate more power, which is required to handle the additional speed and fulfil the power demand. Increased engine speed necessitates more injected liquid fuel, resulting in a higher cylinder burning gas temperature and extended CD. As a result, late combustion aids fuel combustion during the expansion stroke period. The contribution of this heat to engine activity is minimal, increasing EGT as engine speed increases [62]. The EGT increased by 0.19–7.91% for the turpentine and oxygenated turpentine additives in the fuel blends at all engine speeds, as shown in the graph. OTD showed the highest improvement of EGT at 1,800 rpm with a value of 394.58 °C, which is 7.91% higher than D (365.7 °C). According to a prior study, a large percentage of longer-chain fatty acids in a biofuel's chemical makeup resulted in the late combustion of these components and higher EGT [63].

However, at most of the engine speeds, D has the highest EGT, while OAPD has the lowest EGT. When the engine was operated on D, TD, OTD, APD, and OAPD, the maximum EGTs were 477.48 °C, 474.88 °C, 479.43 °C, 433.65 °C, and 381.69 °C, respectively, as observed at the maximum engine speed. The decrease of EGT compared to D is 0.55%, -0.41%, and 9.18% for TD, OTD, and APD, respectively. The highest reduction of EGT recorded at 2,400 rpm was 20.06% for OAPD. The additives in the fuel blend and engine speed have a significant impact on the EGT, as indicated by the changes in EGT. The slow combustion (late or extended combustion) of D is a factor that influences the decrease in EGT with the addition of its additives. This could be due to the additive-diesel blends' higher heat loss, as evidenced by their lower BTE compared to diesel fuel. The leading cause of the drop in EGT is the lower viscosity and volatility of turpentine oil, which leads to improved atomization and evaporation of the injected fuel. As a result, more fuel is prepared during the initial combustion stage. Due to the lower cetane number of turpentine, the available time for fuel preparation during the ID period also increases. As a result, more fuel is consumed in the premixed combustion phase, while less fuel is burned in the later stage of combustion (diffusion combustion phase), resulting in a decrease in EGT.

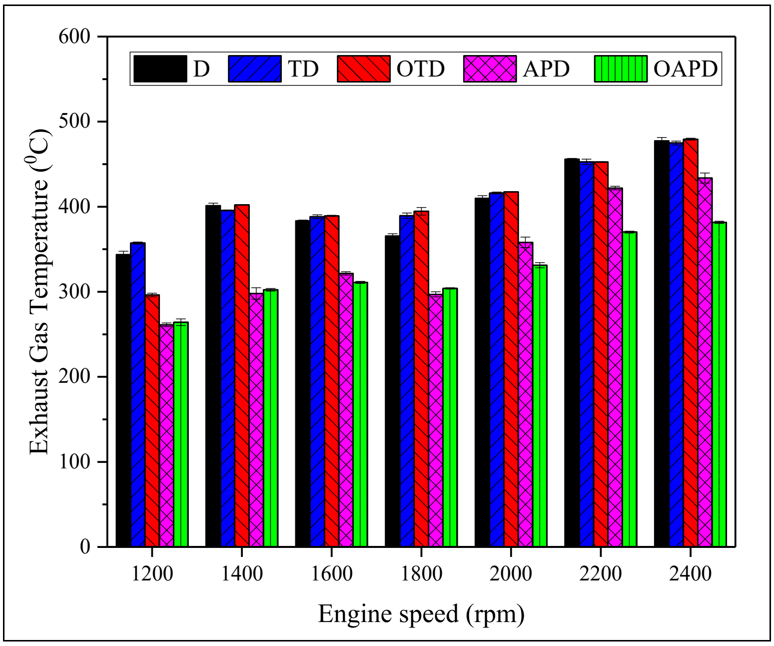

Figure 7: Effect of engine speed on the engine EGT of test fuels at high load

Furthermore, increased combustion of the fuels due to the presence of chemically bonded O_2 content in turpentine-based oil may be another explanation for the decrease in EGT for additive-diesel blends. Moreover, the heat from exhaust gases decreased, producing higher oxygenated additive-diesel blends' BTE than diesel fuel [64]. Other researchers found comparable results using different types of additives [65].

4. Conclusion

This study evaluated the performance of an engine using diesel blended with turpentine oil, alpha-pinene oil, and oxygenated additives under high-load conditions at varying engine speeds. The results demonstrate that additive diesel blends can enhance engine performance while optimising fuel consumption and emissions.

a. Brake Power (BP): At 1,800 rpm, alpha-pinene diesel (APD) achieved the highest BP improvement of 7.33% compared to diesel, reaching 10.67 kW at 2,400 rpm.
b. Brake Torque (BT): The highest BT was recorded by APD at 1,800 rpm with an improvement of 7.33%, reaching 26.10 Nm. However, oxygenated blends slightly reduced BT due to increased combustion pressure.
c. Brake Thermal Efficiency (BTE): Turpentine diesel (TD) achieved the highest BTE of 24% at 1,800 rpm, surpassing the baseline diesel (22.19%). Oxygenated alpha-pinene diesel (OAPD) was also significantly enhanced (23.79%).
d. Brake Specific Fuel Consumption (BSFC): The lowest BSFC was observed with APD at 1,200 rpm, showing a 10.43% reduction compared to diesel. At 1,800 rpm, TD demonstrated an 8.00% improvement over diesel.
e. Exhaust Gas Temperature (EGT): The highest EGT was observed at 2,400 rpm, where oxygenated turpentine diesel (OTD) reached a temperature of 479.43°C. However, oxygenated blends, particularly OAPD, showed an EGT reduction of 20.06% at high speeds.

Using turpentine oil and alpha-pinene oil in diesel blends improves engine efficiency, enhances power output, and reduces fuel consumption. Oxygenated additives further optimise combustion but may slightly impact torque. These findings highlight the potential of alternative diesel formulations in improving engine sustainability and performance.

Acknowledgement

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