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Original Research

Performance of a Single Cylinder Direct Injection 4-Stroke Diesel Engine Under Effect of Using Diesel and Naphtha Blends

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Abstract

The demand for diesel fuel in the transport industry is expected to rise due to greenhouse gas laws and global economic expansion, necessitating the search for alternative energy sources. If light distillate fuels can match diesel fuel's efficiency and cleanliness at a more affordable cost, they could potentially enter the market. The aim of the investigations was to assess a single cylinder, four stroke diesel engine's performance using various blends of diesel (D) and heavy naphtha (N): D100%, D97.5%N2.5%, D95%N5%, D92.5%N7.5%, and D90%N10%. Tests were conducted at 3000 rpm and variable loads, revealing that the maximum permissible naphtha content in diesel oil (D100%) is 10%. Higher naphtha proportions led to misfire and instability under heavy loads. 100% diesel demonstrated the lowest brake-specific fuel consumption and higher thermal efficiency, while mixture of 90% diesel and 10% naphtha showed the highest fuel consumption and lower thermal efficiency.

Keywords: internal combustion engine, diesel engine, additives, engine performance, engine efficiency

1. Introduction

Diesel engines offer superior fuel efficiency, lower CO_2 emissions, and excellent driving performance compared to gasoline engines, mainly due to their lower fuel consumption per unit of output power (Chang et al., 2012; Gupta, 2012). Moreover, diesel engines boast the highest heat efficiency among internal combustion engine types, thanks to their high compression ratio, making them versatile for various applications and sizes. However, with the increasing global population and automobile usage, there is a growing need to reduce fossil fuel consumption (Pan et al., 2020; Yilmaz, 2020).

To address this challenge, researchers are exploring new technologies, combustion modes, alternative fuels, vehicle technology, and additives. One promising substitute for diesel (D) fuels is inexpensive refinery product naphtha (N), which emits fewer CO_2 and NOx during combustion and refinement. Several studies have been conducted on the use of naphtha in compression ignition engines (Mohamad et al., 2018; Mohamad & Zelentsov, 2019; Zhang et al., 2016a).

Ashour et al. (2020) examined the impact of adding 5%, 10%, and 15% naphtha to conventional diesel fuel D100 and biodiesel B30 in a four-stroke, single-cylinder, air-cooled diesel engine under different loads. They found a slight increase in brake specific fuel consumption with D95N5 compared to conventional diesel, and this consumption increased with higher naphtha content. Naphtha had a slight effect on the specific fuel consumption of the B30N5 mixture. Additionally, naphtha reduced nitrogen oxide emissions for the B30N5 mixture under all loads, and CO_2 emissions decreased for the diesel-naphtha blend, while CO2 emissions increased for the B30N5 mixture. The study determined that the maximum permissible percentage of naphtha was 10% for D100 and 5% for B30. Akihama et al. (2009) investigated the limitations of naphtha in achieving the greatest engine power due to significant ignition delay, leading to increased premixed combustion impact, noise levels, and peak in-cylinder pressure. Wang et al. (2014) studied the impact of gasoline and naphtha on multi-premixed combustion igniting mode in a diesel engine with a single-cylinder and 16.7 compression ratio. Multiple premixed compression ignition (MPCI) fuelled with both gasoline and naphtha demonstrated low combustion noise and high efficiency with low exhaust gas recirculation (EGR) ratio and high load. Zhang et al. (2016b) examined how heavy and light naphtha fuels affected combustion and performance in a 6-cylinder diesel engine, showing relatively low soot and NO_x emissions compared to extremely low sulfur diesel. Javed et al. (2016) investigated the auto-ignition properties of low-octane fuel light naphtha, finding that the multi-component surrogate closely matched the light naphtha ignition delay under specific conditions. Vallinayagam et al. (2018) analyzed combustion uniformity and its impact on soot production for partially premixed combustion (PPC) and dieseline fuels in compression ignition (CI) and naphtha modes. Naphtha enhanced combustion uniformity, resulting in almost negligible soot emissions in PPC mode and reduced soot emissions in CI mode compared to dieseline. The use of naphtha as a fuel for typical CI engines presents significant disadvantages, primarily due to its low flash temperature and poor ignition quality, which can result in fire hazards during handling and storage. Additionally, naphtha's low lubricity and kinematic viscosity necessitate the use of lubricity additives to ensure proper fuel pump lubrication.

This study aimed to explore the impact of naphtha-diesel fuel blends on diesel engine performance and compare it with pure diesel fuel. The experiments were conducted at a fixed engine speed of 3000 rpm. Engine operating limitations were established based on factors such as power output, brake-specific fuel consumption and brake thermal efficiency.

2. Experimental setup

This section provides an overview of the experimental setup, test fuels, and the test engine used in the study. The investigation utilized a single cylinder, four stroke, normally aspirated diesel engine with direct injection. The tests were carried out at the Internal Combustion Machinery Laboratory located within the Department of Fuel and Energy Technologies Engineering Techniques at the Technical College of Kirkuk.

2.1. Test engine

The experimental tests utilized a single-cylinder, four-stroke diesel engine operating on conventional diesel fuel. This engine was coupled with an electric generator and various measuring instruments to monitor crucial parameters. These instruments measured the incoming air flow, fuel consumption rate, current, voltage of electric loads, and engine rotational speed. Figure 1 depicts the test setup with the mentioned devices and measuring instruments.

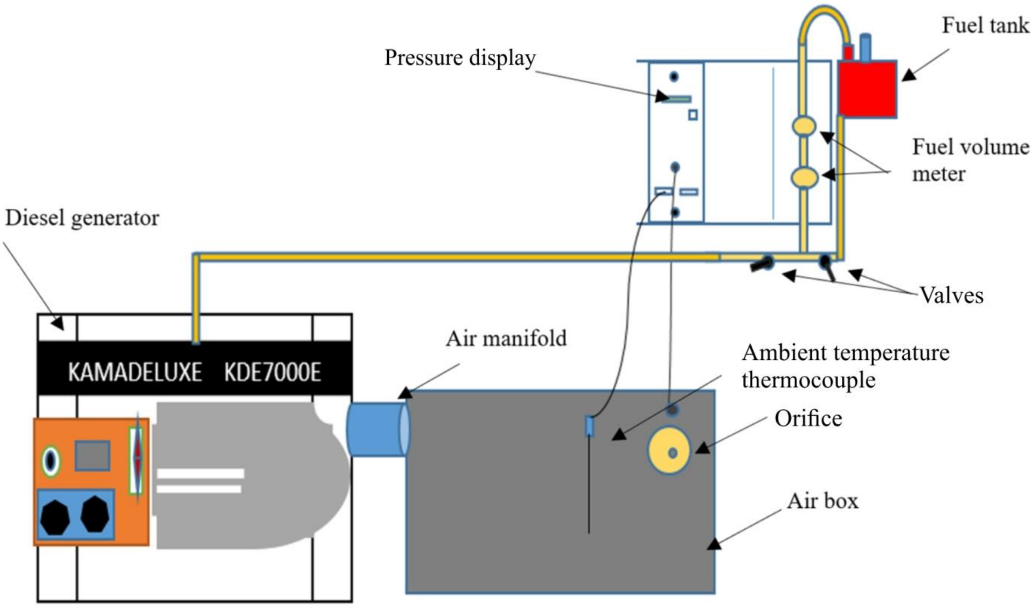

Fig. 1. Test stand.

The engine is manually started by delivering the fuel at a higher level than the engine to ensure a smooth flow towards the mechanical fuel pump. The fuel is then compressed and transformed into a mist to facilitate ignition inside the combustion chamber. The high pressure within the combustion chamber leads to automatic combustion. Table 1 provides an overview of the characteristics of the diesel engine utilized in the laboratory tests.

Table 1. Test engine specification.

Parameter	Value
Cylinder diameter	86 mm
Cylinder number	1
Stroke (s)	72 mm
Connecting rod length (L)	125 mm
Compression ratio	14
Intake valve closing	30 aBDC
Exhaust valve opening	50 bBDC

In an experimental setup, maintaining a consistent and controlled diesel fuel supply is essential for accurate testing of various aspects of diesel engine performance. This is achieved through an automatic regulation system, which ensures that the desired fuel flow rate is maintained. A sensors of system begins by incorporating sensors that monitor critical parameters. In this context, a flow rate sensor is used to measure the actual fuel flow rate. Setpoints used as target fuel flow rate, known as the setpoint, is established. This is the value the control system aims to achieve and maintain throughout the experiment. An appropriate controller, which can be a microcontroller or a programmable logic controller (PLC), is employed. Its primary function is to compare the actual fuel flow rate (sensed by the sensor) with the setpoint.

A controller algorithm utilizes a control algorithm, often a proportional-integral-derivative (PID) controller. This algorithm calculates necessary adjustments required to align the actual fuel flow rate with the desired setpoint. It does this by considering the error, which is the difference between the setpoint and the actual value, as well as historical error information. An actuator, such as a fuel injector or a valve, is connected to the output of the controller. The actuator is responsible for physically adjusting the fuel supply to the diesel engine, based on the instructions provided by the controller.

Continual monitoring of the fuel flow rate via the sensor is done by feedback loop. The sensor data is fed back to the controller in real-time. In response, the controller makes immediate adjustments to the actuator to bring the actual fuel flow rate back in line with the setpoint.

The control system's parameters, including proportional, integral, and derivative gains in a PID controller, are finely tuned to ensure stable and precise regulation of the fuel supply. Rigorous testing of the setup is carried out, and the system is calibrated to ensure it accurately responds to changes in the setpoint, maintaining a consistent and controlled fuel supply.

2.2. Fuels and additives

The fuel that this research investigates includes diesel fuel and naphtha, which is produced by distilling crude oil without any additional processing. The choice of naphtha is intended to take into account a significant portion of naphtha fuels generated by refineries around the world. In this study, the different ratios of diesel fuel and naphtha have been utilize to find out the effect of these ratios of additives on performance parameters such as power, efficiency and specific fuel consumption of a single cylinder four stroke diesel engine. The properties of the diesel and naphtha utilized in this study are shown in Table 2.

Table 2. Physical propertise of diesel and naphtha blends.

Fuel	Density, kg/cm^3	Low heating value, MJ/kg
D100%	853.0	44.8
N100%	671.0	42.2
D97.5%N2.5%	848.3	44.75
D95%N5%	843.6	44.70
D92.5%N7.5%	839.3	44.65
D90%N10%	835.7	44.59

The test engine operates initially on conventional diesel fuel (D100%) without any load, allowing a 30-minute stabilization period to ensure accurate readings, which are sensitive to load changes. The required data, including engine speed, fuel consumption, and pressure difference, are then recorded.

To apply loads, an electric heater is activated, raising exhaust gas temperature, increasing fuel consumption, and causing a slight decrease in electrical voltage while elevating electrical current. With each increase in applied load, data across all parameters change accordingly.

After recording data for conventional diesel (D100%), the tank is emptied, and a mixture of naphtha and conventional diesel is used as a fuel (D97.5%N2.5%). The engine is run without load, and data for this mixture are recorded. Subsequently, the applied load is gradually increased. The same procedure is repeated for mixtures (D95%N5%, D92.5%N7.5%, D90%N10%), and all relevant data are collected. Diesel engines often operate with a relatively high excess air coefficient across a wide range of loads. This is due to the nature of diesel combustion, which relies on spontaneous ignition caused by high compression ratios.

As load increases in diesel engines, the excess air coefficient may decrease slightly to optimize combustion efficiency, but it generally remains higher than in gasoline engines.

The brake power (BP) is calculated by multiplying the current (I) and voltage (V) of the electric generator connected to the engine, taking into account a generating efficiency of 80% as per the equation provided by (Chang et al., 2013).

$$\mathrm{BP} = \frac{\mathrm{I} \times \mathrm{V}}{1000}\,\mathrm{kW} \tag{1}$$

The brake specific fuel consumption (BSFC) is obtained by calculating the mass flowrate of the fuel ($\dot{m}_\mathrm{f}$) measured in units like kilograms per second (kg/s) and brake power that was previously found. The mass flowrate of fuel $\dot{m}_\mathrm{f}$ can be calculated using the following equation (Lata et al., 2012):

$$\dot{m}_\mathrm{f} = \rho_\mathrm{f} \times Q_\mathrm{f} \tag{2}$$

where ρ_f symbolizes the density of the fluid and is measured in units like kilograms per cubic meter (kg/m^3) and Q_f represents the volumetric flow rate of the fluid and is typically measured in units like cubic meters per second (m^3/s). The brake specific fuel consumption calculated from the following equation:

$$\mathrm{BSFC} = \frac{\dot{m}_\mathrm{f}}{\mathrm{BP}} \times 3600 \tag{3}$$

Air (A) to fuel (F) ratio (A/F) is calculated from dividing mass of air ($\dot{m}_\mathrm{a}$) by mass of fuel from the following equation (Mohamad et al., 2020):

$$\frac{\mathrm{A}}{\mathrm{F}} = \frac{\dot{m}_\mathrm{a}}{\dot{m}_\mathrm{f}} \tag{4}$$

Then the braking thermal efficiency (BTE) monitored, which is the ratio of the brake power generated by the engine to the thermal energy of the fuel from the following equation (Heywood, 2018):

$$\mathrm{BTE} = \frac{\mathrm{BP}}{\dot{m}_\mathrm{f} \times Q_\mathrm{H.V}} \times 100\% \tag{5}$$

where Q_HV symbolizes the heating value of the fuel, often referred to as the lower heating value (LHV) or higher heating value (HHV). It is typically measured in units like joules per kilogram (J/kg).

3. Results and discussion

The results of the practical tests conducted on a single cylinder, four stroke diesel engine, using different volumetric ratios of mixtures consisting of conventional diesel fuel and medium-density naphtha, are presented and discussed in Table 2. The engine was operated under various loads and the same operating conditions. Performance parameters, such as power, brake specific fuel consumption (BSFC), and braking thermal efficiency, were studied for each volumetric ratio (D97.5%N2.5%, D95%N5%, D92.5%N7.5%, D90%N10%).

Figure 2 illustrates the relationship between brake power and brake thermal efficiency for diesel fuel and the various mixtures of diesel and naphtha. The results reveal that brake thermal efficiency increases with increased brake power at low and moderate loads. However, at high loads where the brake power is increased, the brake thermal efficiency decreases. The highest brake thermal efficiency is achieved with conventional diesel fuel, followed by D97.5%N2.5%, D95%N5%, D92.5%N7.5%, and D90%N10%, respectively.

For instance, at a power output of 3.740 kW, it is observed that the brake thermal efficiency of pure diesel fuel surpasses that of all mixtures (D97.5%N2.5%, D95%N5%, D92.5%N7.5%, D90%N10%) with the following ratios: 4%, 7.9%, 12.09%, and 16.24%, respectively.

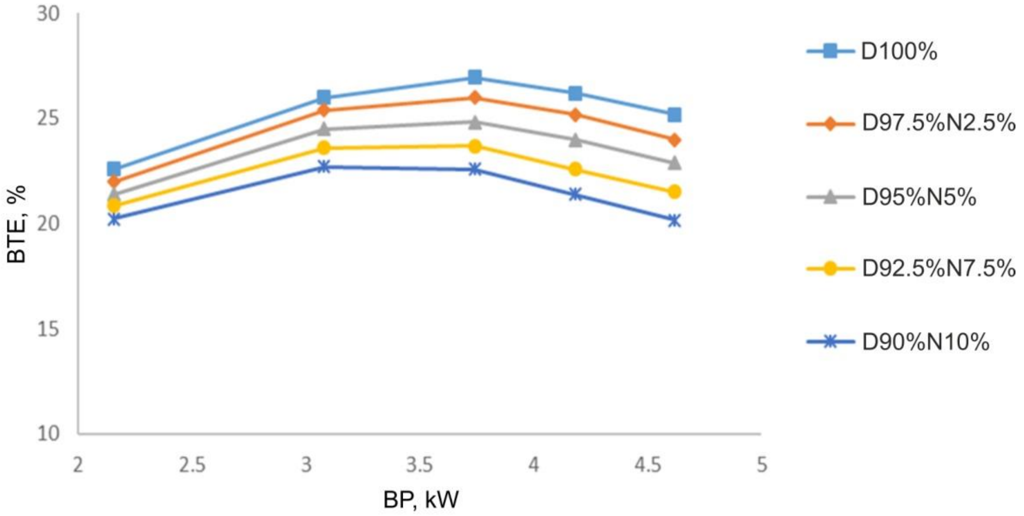

Fig. 2. The relation between brake power and BTE.

Figure 3 illustrates the relationship between BSFC and brake power for both conventional diesel fuel and diesel-naphtha mixtures. It is evident that BSFC decreases with increasing brake power at low loads, but it increases as the brake power is applied at high loads. Moreover, specific fuel consumption rises with higher proportions of naphtha added to diesel fuel, with conventional diesel fuel (D100%) exhibiting the lowest specific fuel consumption compared to all diesel-naphtha mixtures. Notably, D90%N10% has the highest specific fuel consumption among the mixtures (D100%, D97.5%N2.5%, D95%N5%, D92.5%N7.5%). To understand the specific reasons for the significant difference in BTE between the fuels with similar calorific values, detailed testing and analysis of the combustion process, engine parameters, and fuel properties are necessary. Adjustments to the engine's operating parameters and fuel delivery may be needed to optimize BTE for each fuel type.

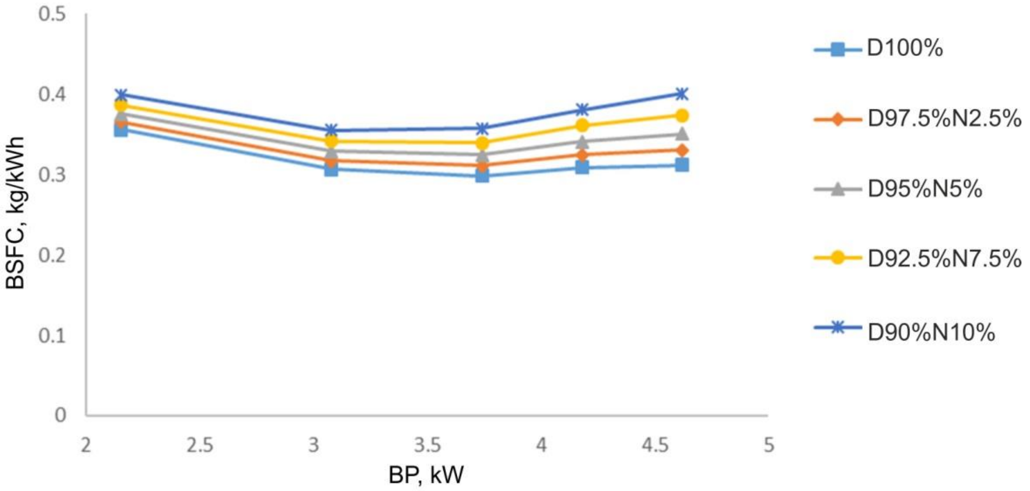

Fig. 3. The relation between brake power and BSFC.

Analyzing the data from the figure, it can be observe that at a power output of 4.180 kW, the specific fuel consumption of pure diesel fuel (D100%) is lower than the mixtures (D97.5%N2.5%, D95%N5%, D92.5%N7.5%, D90%N10%) in the following proportions: 4.77%, 9.36%, 14.46%, and 19.46%, respectively. This is primarily due to conventional diesel fuel's higher density and calorific value compared to all the diesel-naphtha mixtures.

Figure 4 displays the relationship between the air-to-fuel ratio and brake power. A comparison between conventional diesel fuel and diesel-naphtha mixtures reveals that the highest air-to-fuel ratio is achieved when using pure D100% at the lowest load. At the lowest load (2.156 kW), the air-to-fuel ratio shows an increase of (2.38%, 4.76%, 7.45%, 10.36%) compared to all diesel-naphtha mixtures (D97.2%N2.5%, D95%N5%, D92.5%N7.5%, D90%N10%) respectively, and this ratio increases with higher loads. Conversely, the lowest air-to-fuel ratio is observed when using D90%N10% at the highest load. Consequently, the brake-specific fuel consumption increases with higher loads and the percentage of added naphtha.

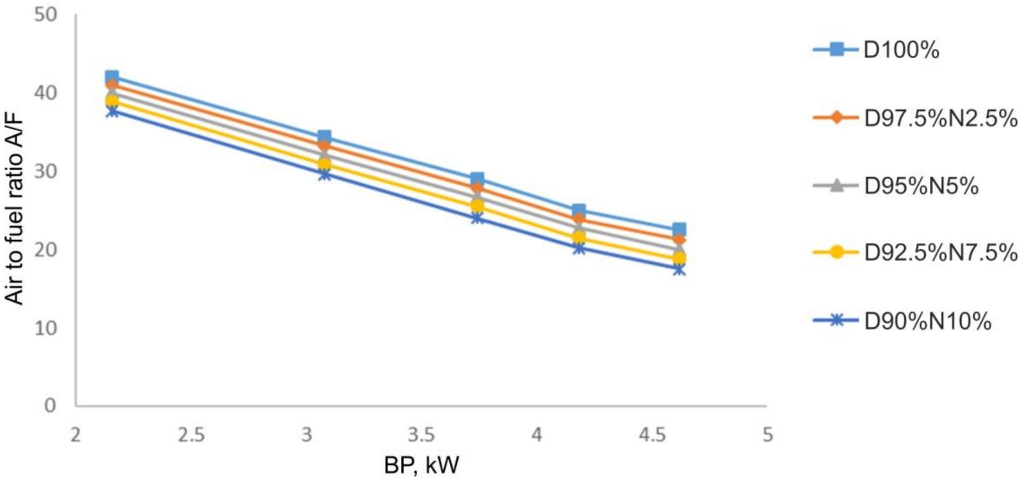

Fig. 4. The relation between A/F and brake power.

4. Conclusions

In this research, the effect of adding naphtha to conventional diesel fuel was studied, and the impact of this addition on brake specific fuel consumption, thermal efficiency, and the air-to-fuel (A/F) ratio was examined at a constant speed of 3000 rpm. The results obtained indicate that 10% was the highest proportion that could be added to D100%. Further increasing the percentage of naphtha caused the engine to misfire and operate unstably under heavy loads. It became evident that the brake specific fuel consumption and air-to-fuel ratio decrease with the increase of the load applied to the engine. Moreover, the increase in the percentage of naphtha added to diesel fuel led to an increase in the brake specific fuel consumption rate. The results of this study concluded that the lowest specific consumption rate and highest air-to-fuel ratio and thermal efficiency are observed when using diesel fuel, followed by D95%N5%, and then D90%N10%, respectively. Numerous experiments that fall outside the purview of this paper's discussion can help understand how to use naphtha in CI engines when blended with diesel. In order to enhance the proportion of naphtha added to diesel fuel D100% that is permitted, it may be beneficial to investigate the impact of increasing injection time.

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Wydajność Jednocylindrowego 4-Suwowego Silnika Wysokoprężnego z Bezpośrednim Wtryskiem Paliwa Zasilanego Mieszaniną Oleju Napędowego i Benzyny Ciężkiej

Streszczenie

Oczekuje się, że zapotrzebowanie na olej napędowy w branży transportowej będzie zwiększało się ze względu na przepisy dotyczące gazów cieplarnianych i globalną ekspansję gospodarczą, co wymusza poszukiwanie alternatywnych źródeł energii. Jeżeli lekkie destylaty będą w stanie dorównać wydajności i czystości olejowi napędowemu, przy bardziej przystępnej cenie, mogłyby potencjalnie zostać wprowadzone na rynek. Celem badań była ocena osiągów jednocylindrowego, czterosuwowego silnika wysokoprężnego stosując różne mieszanki oleju napędowego (D) i benzyny ciężkiej (N): D100%, D97.5%N2.5%, D95%N5%, D92.5%N7.5% i D90%N10%. Badania przeprowadzono przy 3000 obr/min i zmiennym obciążeniu. Wykazano, że maksymalna dopuszczalna zawartość benzyny ciężkiej w oleju napędowym wynosi 10%. Większa zawartość benzyny w oleju napędowym prowadziła do przerw w zapłonie i niestabilności pod dużym obciążeniem. 100% olej napędowy wykazał najniższe zużycie paliwa przy hamowaniu i wyższą sprawność cieplną, podczas gdy mieszanina 90% oleju napędowego and 10% benzyny ciężkiej wykazała najwyższe zużycie paliwa i niższą sprawność cieplną.

Słowa kluczowe: silnik wewnętrznego spalania, silnik wysokoprężny, dodatki, osiągi silnika, sprawność silnika