ANALYSIS OF PRE-INJECTION RATE EFFECTS ON COMBUSTION, PERFORMANCE, AND EMISSIONS IN A JP8-FUELED PPCI ENGINE

by

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In this study, the effects of varying pre-injection rates (10%, 20%, 30%, 40%) on engine performance, combustion efficiency, and emissions were investigated in a partial premixed compression ignition (PPCI) engine using JP8 fuel at various loads (0%, 25%, 50%, 75%, and 100%) and compared with diesel fuel. A 10% pre-injection rate was most effective in maintaining fuel efficiency across loads, showing the lowest BSFC values. At 50% load, the 10% rate resulted in a brake specific fuel consumption of 294.22 g/kWh, only 9.69% higher than diesel. Higher rates (30% and 40%) increased fuel consumption and decreased efficiency. Combustion efficiency and CO_2 emissions improved with 20% and 30% rates, especially at high loads. At 75% load, 30% pre-injection increased CO_2 emissions to 8.827%, exceeding diesel 7.88%, indicating better combustion. Soot emissions decreased significantly with 30% and 40% rates, but NO_x emissions rose substantially, with the 40% rate reaching 1448 ppm at full load. The 10% rate was deemed optimal for balancing efficiency and low emissions, while higher rates, though beneficial for combustion and soot, require measures to mitigate NO_x emissions.

Key words: *PPCI, JP8, pre-injection, engine performance, exhaust emissions, combustion*

Introduction

The quest to improve the efficiency, performance and environmental impact of internal combustion engines has stimulated a variety of research, including the development of alternative fuels and the adaptation of existing engine technologies to these fuels [1, 2]. Fuel standardization is of great importance, especially for military vehicles, to ensure operational efficiency and reduce the logistical burden in the field. The NATO aims to implement a fuel standardization policy called the *Single Fuel Concept* in military operations [3]. This approach aims to increase operational efficiency and simplify logistical processes by using a single type of fuel in all military vehicles [4, 5]. In this context, JP8 fuel has become the main

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fuel preferred by NATO and other military forces. The usability of JP8 in land, air and sea vehicles significantly reduces the logistic burden while also facilitating fuel supply. The JP8 fuel is basically a kerosene-based jet fuel and has been formulated specifically for military applications. The JP8 is similar to the civil jet fuel Jet A-1, however, it contains some additives to meet military requirements. These additives offer features such as preventing freezing at low temperatures, increasing corrosion resistance and ensuring safety. One of the most important reasons for preferring JP8 is its compatibility with different engine types. The JP8, which can be used in both jet and Diesel engines, increases operational flexibility in the military field thanks to its versatility and allows all military vehicles to operate with a single fuel. This offers a great advantage in crisis regions or areas with limited logistics. However, in addition to all these advantages of JP8, making it compatible with Diesel engines involves some technical difficulties [6-8]. The JP8 has a lower cetane number compared to diesel fuels [9]. The cetane number indicates the ability of a fuel to self-ignite and directly affects the combustion process in Diesel engines [10]. The low cetane number of JP8 can also provide an opportunity to solve the problem of premature ignition in partial premixed combustion mode [11]. The low cetane number means that JP8 can cause delayed ignition in Diesel engines, which can negatively affect combustion efficiency [12]. In addition, the low lubricity of JP8 can cause wear in the fuel injection systems of Diesel engines, which can shorten engine life [13, 14]. Such disadvantages necessitate various engineering solutions and adaptations for the effective and long-lasting use of JP8 in Diesel engines. Another important technology for Diesel engines, PPCI systems, is considered a promising solution to optimize the use of JP8. The PPCI contributes to the homogenization of the combustion process by mixing the fuel with a certain amount of air before compression [15, 16]. This method helps reduce harmful emissions such as NO_x by reducing the combustion temperature, while ensuring that the fuel burns more efficiently [17, 18]. The PPCI is increasingly being investigated with JP8 to achieve optimal performance and low emissions in Diesel engines. However, PPCI makes the combustion process more complex and requires precise injection strategies and engine calibration to work with JP8.

The premixed charge compression ignition (PCCI) and partially premixed combustion (PPC) strategies have gained significant attention for their potential to reduce NO_x and particulate emissions in Diesel engines. Advanced injection strategies, such as dual injection and early pilot injection, have been shown to enhance fuel-air mixing, reducing peak combustion temperatures and emissions while maintaining efficient combustion [19]. Studies on spray-wall interaction and fuel trapping effects in PPC have demonstrated that injection timing significantly influences combustion efficiency and CO emissions [20]. Similarly, Atkinson cycle-based PCCI combustion has been explored to extend the operational range of low-emission combustion strategies while maintaining fuel economy [21]. Biodiesel blends have also been investigated for PCCI applications, revealing that higher biodiesel content improves emissions performance, particularly for NO_x and soot reduction, although particulate formation can be affected by fuel-air mixing characteristics [22]. Overall, the integration of advanced injection strategies, alternative fuels, and optimized operating parameters plays a crucial role in achieving low-emission, high-efficiency combustion in modern Diesel engines [23].

In this study, the effects of JP8 fuel on combustion characteristics, engine performance, and exhaust emissions in Diesel engines operating with the PPCI system were investigated. Combustion parameters such as ignition delay, maximum cylinder pressure, and heat release rate were examined in detail. The low cetane number of JP8 may extend ignition delay, making combustion control more difficult and potentially affecting engine efficiency and performance. In terms of engine performance, the study evaluated thermal efficiency, brake specific fuel consumption (BSFC), and power output. Thermal efficiency reflects the proportion of fuel energy converted into useful work, while BSFC indicates the fuel required to generate unit power. This parameter is particularly important for military applications, where high power output and operational efficiency are critical. The performance of JP8 under PPCI conditions was compared to standard diesel, highlighting both strengths and limitations. Regarding exhaust emissions, the study focused on NO_x, CO, HC, and PM emissions. Although the PPCI strategy can help reduce NO_x formation by lowering peak combustion temperatures, JP8 ignition characteristics may compromise combustion stability and increase emissions. The PM emissions, a major concern for air quality and human health, were also evaluated based on JP8 combustion behavior.

In conclusion, the study provides a comprehensive analysis of JP8 applicability in PPCI-compatible Diesel engines. While JP8 offers logistical and operational advantages for military use, it also introduces technical and environmental challenges. Optimizing combustion strategies and developing emission control solutions are essential for its effective integration. The findings aim to contribute to the literature and guide future research on the use of alternative fuels in advanced combustion systems.

Materials and methods

This study was conducted on a partial premix compression ignition engine using JP8 fuel. The experiments were carried out in Sakarya Applied Sciences University Arifiye Vocational School Engine Test and Simulation Laboratory. In the study, two injection systems were used, namely main injector and port injector, and pre-injection ratios were determined as 10%, 20%, 30%, and 40%. Port injection timing and diesel injector timing were kept constant throughout the experiments, and the engine was tested at 1800 rpm and 0%, 25%, 50%, 75%, and 100% engine loads. The engine was operated in conventional mode with standard diesel fuel and data were collected. Then, data were collected by operating it in PPCI mode with JP8 fuel at the same speed and engine loads with different pre-injection ratios. In addition, the engine was operated with standard diesel fuel and tested for the same engine loads. As a result of the tests, comparisons were made between standard diesel fuel and JP8 fuel. The physical properties of JP8 and diesel fuels used in the experiments are given in tab. 1.

Table 1. Physical properties of JP8 and diesel fuels [24]

Properties	JP8	Diesel
Density (kg/L, 15 °C)	0.7950	0.8372
Cetane number	45	54
Lower heating value [$MJkg^{-1}$]	43.2	44-46
Flash point [°C]	41	73
Viscosity [cSt]	3.87 (40 °C)	2.8 (40 °C)

Diesel fuel is slightly denser than JP8. The higher density can offer more energy potential per unit volume, which is important for energy efficiency. Diesel fuel has a higher cetane number than JP8. The higher cetane number can increase combustion efficiency and allow faster ignition. The lower cetane number of JP8 can lead to delayed combustion and potentially lower thermal efficiency. Diesel fuel has a slightly higher energy content than JP8. This means that diesel offers more energy per unit weight. The JP8 has a lower flash point than diesel, meaning that JP8 is more ignitable. However, the lower flash point means that JP8 can be more flammable, especially in hot conditions. The JP8 has a lower viscosity than diesel fuel. The lower viscosity can lead to wear in the injection system due to the thinner structure of the fuel. The JP8 has a lower sulphur content, meaning lower emissions. Diesel fuel, on the other hand, varies in terms of sulphur content. The combustion temperature of diesel is slightly higher than that of JP8, meaning that more heat can be produced with the same amount of fuel. The flash point of both fuels is similar, which is an important feature in terms of safety. The JP8 generally has a higher carbon content, while its ash content is lower. This indicates that JP8 may cause more carbon emissions. The experiments were conducted on a single-cylinder, air-cooled Antor 3LD510 Diesel engine with a 510 cm³ displacement, an 85 × 90 mm bore and stroke, a compression ratio of 17.5:1, delivering a maximum power of 12.0 hp (9.0 kW) at 3000 rpm and a peak torque of 32.8 Nm at 1800 rpm. In the experiments, JP8 fuel was injected using the port injection system together with the main fuel injector. While the main injector delivers fuel into the engine cylinder by direct injection, the port injection system is placed in the intake manifold. An electronic control unit controls the port injection system and the injection time and amount are adjustable. However, the port and main injection timing were kept constant throughout the test. Only the pre-injection ratio was changed as 10%, 20%, 30%, and 40%. The schematic representation of the experimental set-up is shown in fig. 1.

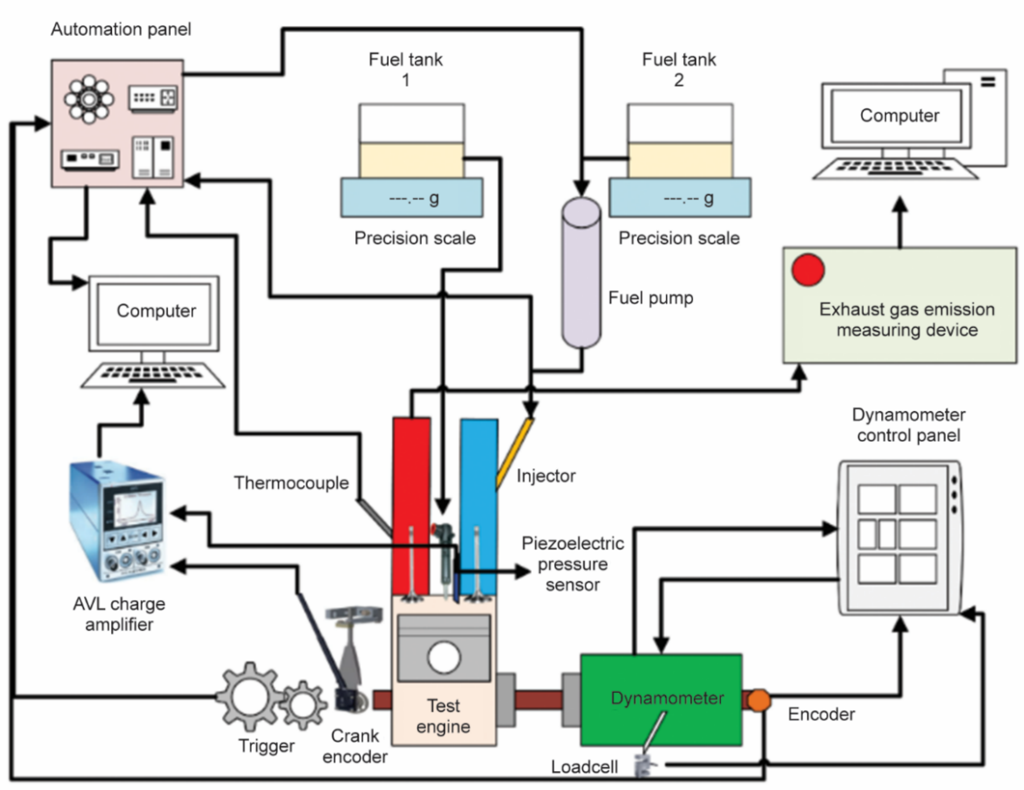


Figure 1. Schematic diagram of test set-up

A KEMSAN brand DC dynamometer with a capacity of 15 kW was used for engine power and torque measurements. A load cell connected to the dynamometer was used to measure the engine load. The consumption of JP8 fuel injected into the engine through the main fuel injector was measured in grams in 60 seconds using a precision scale and a stop-watch. Fuel consumption measurements were repeated at least twice at each test point. In-cylinder pressure measurements were performed using an AVL brand pressure sensor. These measurements were used to calculate the heat release rate, cumulative heat release, CA10 and CA90 parameters. The characteristics of the JP8 fuel injected from the port injector were determined, and the injection amount was determined in grams per second. The exhaust gas temperature was measured with a *K*-type thermocouple mounted on the exhaust manifold. The BILSA MOD 2210 WINXP-K brand device was used as the exhaust gas analyzer. The experiments were carried out at 1800 rpm when the engine produced maximum torque and at 0%, 25%, 50%, 75%, and 100% engine loads. In each test case, main injection and port injection timing were kept constant and 10%, 20%, 30%, and 40% pre-injection rates were applied. Engine load was adjusted via the dynamometer control panel and the engine speed was controlled by a tachometer connected to the dynamometer.

Experimental results

This section evaluates the results obtained for different pre-injection rates with JP8 fuel in the PPCI mode of a Diesel engine. In the study, in-cylinder pressure, heat release rate, cumulative heat release, CA10, CA90, BSFC, thermal efficiency, CO, HC, NO_x, CO_2, and soot emission values are discussed as experimental results.

Figure 2 shows the in-cylinder pressure and heat release graphs according to pre-injection rates. When the graph is examined, it is seen that the study with standard diesel, 10% and 20% JP8 pre-injection rates yielded similar results. However, the results show that increasing the JP8 pre-injection rate to 30% and 40% increased the maximum pressure reached at the end of combustion while causing combustion to start at earlier CA. While the maximum in-cylinder pressure occurred around 70 bar and 7 CA after top dead center with standard diesel, 10% and 20% JP8 pre-injection, it occurred at 80 bar and 85 bar pressures and 3 CA after top dead center with 30% and 40% JP8 pre-injection, respectively. These results show that the effect of making the JP8 pre-injection rate of 10% and 20% on combustion under full load conditions is very little. The results are: It is shown that the JP8 pre-injection at 30% and 40% rates advances the start of combustion, resulting in maximum pressure occurring as early as 4 CA, and the maximum pressure increasing by 21.43%. This situation is thought to be due to

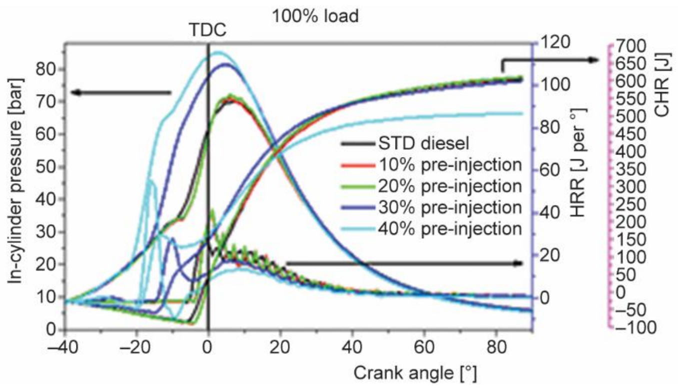


Figure 2. Variation of in-cylinder pressure, heat release rate, and cumulative heat release for different pre-injection rates at full load

the fact that the flash point of JP8, 41 °C, is significantly lower than the flash point of diesel, 73 °C, and that it helps to start combustion early by vaporizing in the compressed air under full load conditions, together with the effect of the temperature in the combustion chamber, and reducing the ignition delay [25].

Figure 3 shows the graphs showing CA10 and CA90 values. When the graph showing CA10 values at 100% load is examined, in accordance with the pressure graph in fig. 2, while the CA10 values show close values around –2 CA in the experimental results with standard diesel, 10% and 20% JP8 pre-injection, it is clearly seen that combustion starts at earlier CA in the results obtained from the experiments with 30% (–12) and 40% (–18) JP8 pre-injection. Similarly, the data at 100% load in the graphs showing CA90 value show that a larger portion of the fuel is burned at earlier CA due to the earlier combustion starts at 30% and 40% JP8 pre-injection rates compared to diesel, 10% and 20% JP8 pre-injection rates. The results indicate that higher pre-injection ratios, especially 30% and 40%, improve combustion timing (CA10) and promote earlier combustion completion (CA90) under high engine loads (75%-100%). This enhances efficiency and power output under demanding conditions. Conversely, at low loads, all pre-injection ratios cause delayed combustion, particularly due to low in-cylinder temperatures and the lower ignition quality of JP8 fuel. At medium loads, combustion benefits are more variable. Only the 40% pre-injection rate shows a consistent advantage in both advancing ignition and shortening combustion duration. Lower pre-injection rates (10%, 20%) generally result in later combustion start and completion across all load levels, which may compromise engine efficiency and performance. Fuel properties such as low cetane number and calorific value contribute to these combustion delays. Literature supports that low cetane fuels typically show longer ignition delays and extended combustion periods, especially under low-temperature conditions [26-28].

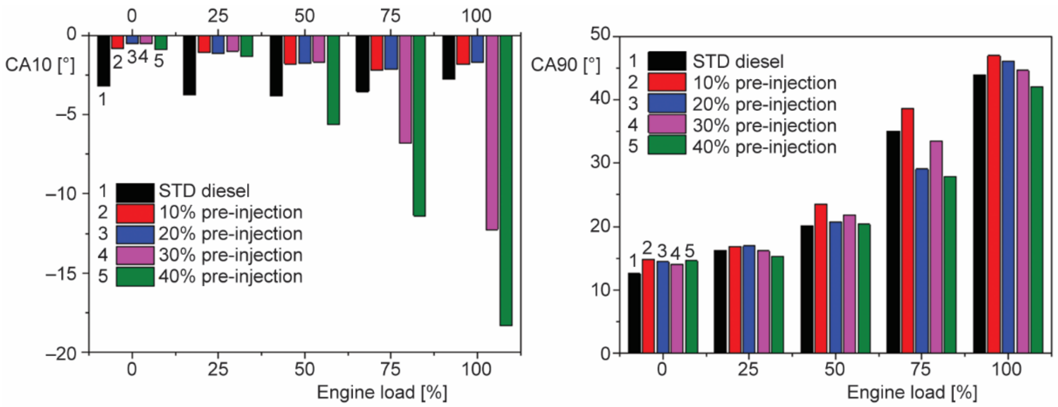


Figure 3. The CA10 and CA90 variations for different pre-injection rates and engine loads

Figure 4 shows the BSFC and thermal efficiency values of JP8 at varying pre-injection rates (10%-40%) and engine loads. In general, 10% pre-injection rate provides the most consistent fuel efficiency. It showed the same efficiency levels as diesel, especially at full load (100%). Both 10% and 30% showed minimum BSFC increases at full load. Especially 40% JP8 pre-injection at full load showed BSFC increase. This result shows that high rate of JP8 pre-injection probably decreases efficiency due to combustion instability. However, at high loads (*e.g.* 75%), 40% pre-injection can increase thermal efficiency through improved pre-mixed combustion. It is seen that lower calorific value and cetane number of JP8 contribute to higher BSFC values compared to diesel. However, it is also seen that it can allow better pre-mixed combustion under certain conditions [29, 30]. The optimum pre-injection strategy is load dependent and 10% generally provides the best balance between fuel economy and efficiency.

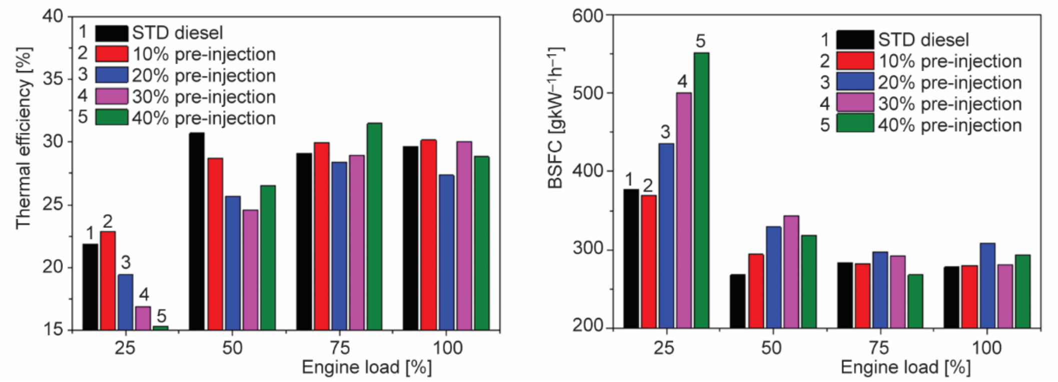
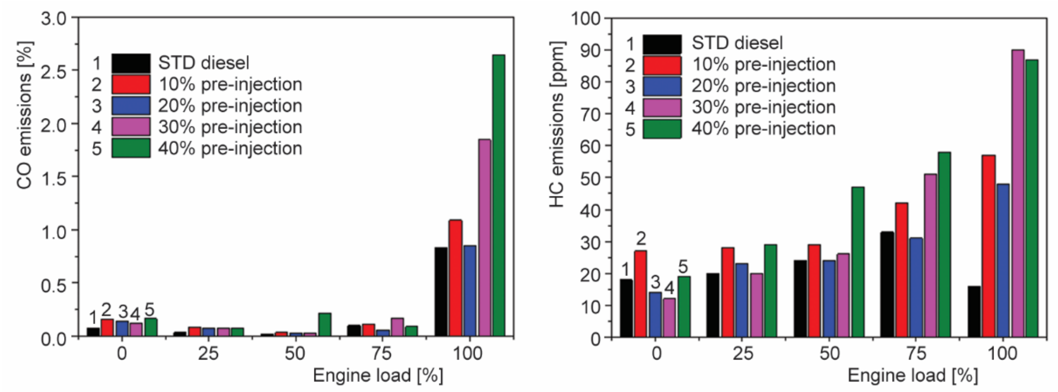


Figure 4. The BSFC and thermal efficiency variation for different pre-injection ratio and engine loads

Figure 5 shows the change in HC, CO, and CO_2 emissions for different engine load levels, pre-injection ratios and standard diesel (STD diesel). The HC emissions varied significantly with engine load and pre-injection rate. At low load (0%-25%), the 20% and 30% pre-injection rates reduced HC emissions compared to standard diesel, with 30% achieving the lowest value of 12 ppm at no load. However, HC emissions increased noticeably with higher pre-injection rates at medium to high loads. At full load (100%), HC levels peaked at 90 ppm and 87 ppm for 30% and 40% rates, respectively, far exceeding the diesel baseline of 16 ppm. In contrast, the 10% rate consistently resulted in higher HC emissions across all loads, suggesting incomplete combustion. These results indicate that while moderate pre-injection (20%-30%) improves HC emissions at low loads, excessive pre-injection or increased load leads to combustion instability and elevated HC formation. The CO emissions generally increased with both load and pre-injection rate. At low loads (0%-50%), diesel showed the lowest CO levels, while all JP8 pre-injection strategies resulted in higher emissions. Notably, the 10% rate produced the highest CO at no load (0.163%), more than double that of diesel (0.073%). At mid-loads (25%-50%), the 20% and 30% rates yielded relatively lower CO among the JP8 cases, suggesting improved combustion efficiency. However, at high loads (75%-100%), CO emissions rose sharply, particularly with higher pre-injection rates. The 30% and 40% strategies exhibited significant increases at full load, reaching 1.848% and 2.644%, respectively, substantially higher than diesel 0.834%. These findings indicate that while moderate pre-injection rates can help maintain lower CO emissions at certain loads, excessive pre-injection, especially under high loads, leads to incomplete combustion and elevated CO production. The CO_2 emissions, an indicator of combustion completeness, generally increased with engine load and pre-injection rate. At low loads (0%-25%), diesel emitted slightly less CO_2 than JP8 blends, with minimal differences among pre-injection rates. As the load increased, CO_2 emissions rose across all cases. At 50% and 75% loads, the 30% pre-injection rate showed the highest CO_2 levels, 5.136% and 8.827%, respectively, exceeding diesel's values and indicating more complete combustion. At full load, all JP8 strategies produced higher CO_2 than diesel (9.491%), with 10% pre-injection peaking at 10.877%, followed closely by other rates. These results suggest that pre-injection, particularly at 30%, enhances combustion efficiency at mid to high loads, but differences among strategies become less significant at full load.



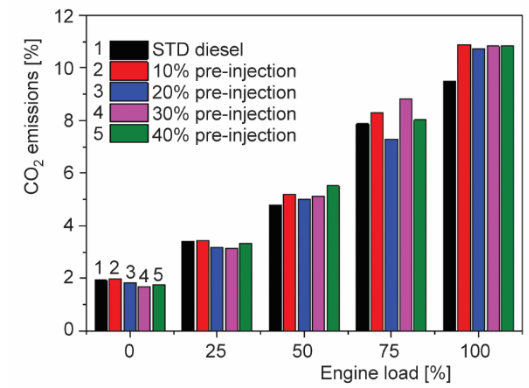


Figure 5. The HC, CO, and CO_2 emissions changes for different pre-injection rates and engine loads

Figure 6 shows the change in NO_x and soot emissions for different engine load levels, pre-injection ratios and standard diesel (STD diesel). The NO_x emissions displayed a clear upward trend with increasing engine load and pre-injection rate. At low loads (0%-25%), all JP8 pre-injection strategies significantly reduced NO_x compared to diesel, with the 40% rate showing the lowest value of 60 ppm at no load. However, at medium to high loads (50%-100%), NO_x emissions rose markedly for higher pre-injection rates. At full load, NO_x peaked at 1448 ppm with the 40% rate, well above diesel 930 ppm. The 10% pre-injection rate showed a moderate increase, reaching 1134 ppm, indicating a better balance between emissions and performance. These results suggest that while pre-injection can effectively suppress NO_x at low loads due to cooler combustion, excessive rates at high loads intensify in-cylinder temperatures and promote NO_x formation. Therefore, careful optimization is necessary to mitigate NO_x without compromising combustion efficiency. Soot emissions were negligible at low and medium engine loads (0%-50%) across all fuel types and pre-injection rates. Differences emerged at higher loads. At 75% load, all pre-injection strategies significantly reduced soot compared to standard diesel (8.57 mg/m^3), with 40% pre-injection eliminating it entirely. At full load (100%), diesel emitted the highest soot (14.41 mg/m^3), while increasing pre-injection rates progressively reduced soot, with the 40% rate achieving the lowest value (5.31 mg/m³). This trend indicates that higher pre-injection rates enhance fuel-air mixing and promote more complete combustion at high loads, effectively suppressing soot formation. Therefore, while higher rates may increase NO_x, they offer clear benefits for reducing particulate emissions under heavy load conditions.

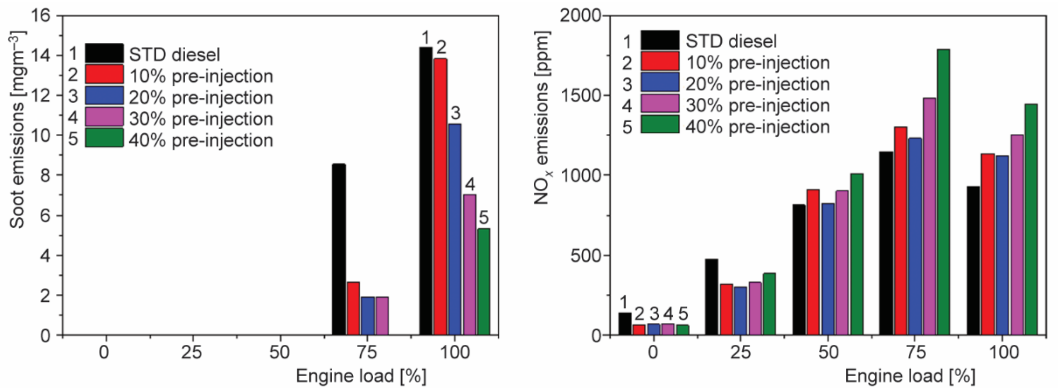


Figure 6. The NO_x and soot emissions variation for different pre-injection rates and engine loads

Conclusions

The JP8 fuel was tested at different engine loads (0%, 25%, 50%, 75%, and 100%) and for different pre-injection rates (10%, 20%, 30%, and 40%). The obtained data were compared with the effects of standard diesel fuel on engine performance, combustion efficiency and emissions.

- The 10% pre-injection rate provided the most positive results, showing BSFC values close to or better than diesel fuel efficiency at most load levels. Higher pre-injection rates generally increased fuel consumption, indicating lower fuel efficiency, especially at low and medium loads. This may be due to the high amount of fuel being sent to the combustion chamber. The reason for the increase in BSFC in JP8 fuel may be that its lower calorific value is lower than standard diesel and it has a lower density. Considering the difference in density and calorific value, it can be considered that the combustion efficiency of JP8 fuel is better than standard diesel at pre-injection rates where it has values close to standard diesel fuel.
- Especially 20% and 40% pre-injection rates reduced CO emissions at high loads and provided more complete combustion. However, higher rates at low and medium loads did not significantly reduce CO emissions or slightly increased them.
- Higher pre-injection rates (30% and 40%) at medium and high loads showed higher CO_2 emissions. This is an indication of more complete combustion. It was observed that pre-injection did not significantly increase CO_2 emissions at low loads.
- Pre-injection increased combustion efficiency by providing generally lower HC emissions at 10% and 20%. However, at full load, all pre-injection rates showed higher HC emissions than diesel fuel, suggesting incomplete combustion under high fuel demand.
- The NO_x emissions increased at medium and high loads (50% and above), especially at high pre-injection rates such as 30% and 40%. This is due to higher combustion tempera-

tures. At low loads (0% and 25%), all pre-injection rates reduced NO_x emissions compared to diesel fuel.

- High pre-injection rates (30% and 40%) significantly reduced soot emissions, especially at high and full loads. This indicates that soot formation is reduced due to better air-fuel mixing and efficient combustion. At low loads, both pre-injection and diesel showed low soot emissions due to sufficient oxygen supply.

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