Reducing the Effect of High Sulfur Content in Diesel Fuel on NO$_x$ Emissions and PM Characteristics Using a PPCI Mode Engine and Gasoline–Diesel Blends

Mohammed A. Fayad, Miqdam T. Chaichan, Hayder A. Dhahad, Ahmed A. Al-Amiery,* and Wan Nor Roslam Wan Isahak*

ABSTRACT: Recently, high sulfur content in diesel fuel is one of the main problems that have an effect on combustion and emission characteristics. Iraq is one of many countries in the world that use diesel fuel with high sulfur content. Therefore, the partially premixed combustion ignition (PPCI) concept and different blend ratios of gasoline–diesel (GD30, GD40, and GD50) were suggested in this study to reduce the sulfur content in the fuel, improve the engine performance, and reduce the exhaust emissions. The combined effect of adding gasoline to the diesel fuel and manipulating the fuel injection timings can lead to better and clean combustion. For the same engine operating conditions, it is found that the brake thermal efficiency (BTE) decreases during the combustion of GD blends in comparison with diesel fuel. Furthermore, the results of using GD blends showed a small reduction in brake-specific fuel consumption (BSFC) compared to the conventional diesel fuel. The exhaust gas temperature reduces from the combination effect of PPCI mode and GD blends, which in turn decreases the NO$_x$ emission concentration under variable conditions of engine loads and speeds. It is indicated that the NO$_x$ emissions significantly decreased during the combustion of GD30, GD40, and GD50 blends by 25.94, 50.9, and 84%, respectively, in comparison with diesel fuel. In addition, higher reduction in CO and HC formation was obtained during the combustion of conventional fuel in comparison with the combustion of GD blends. The results showed that the number and concentration of PM reduced more when using GD blends and PPCI mode. The average particle diameter ($d_p$) decreased from the combustion of GD blends in comparison with diesel fuel. The particle diameter of the GD blend was varied from 25 to 26 nm compared to those of diesel fuel of 35 and 36 nm under the same engine operating conditions. Reducing the sulfur content in GD blends contributed to a clear reduction in SO$_2$ and H$_2$S emissions by 57.85 and 50.12%, respectively.

1. INTRODUCTION

The energy depletion and environmental pollution generated from the transport sector lead to an increase in the strict emission regulation according to the recent investigation on vehicle emissions.$^{1,2}$ Therefore, most of the studies focused on using clean fuel in the transport sector to reduce the negative effect of exhaust emissions on the environment and human health.$^3$ However, cars are essential in everyday life for transportation and power generation over the world. Transition to sustainable mobility is considered possible in the current phase, while minimum emissions and good energetic performance are critical. It is reported that considerable amounts of pollutants such as oxides of nitrogen (NO$_x$), hydrocarbons (HCs), carbon monoxide (CO), and particulate matter (PM) are emitted during engine operation due to high conditions of pressure and temperature required in heavy-duty diesel engines.$^{4,5}$ Furthermore, these exhaust gas emissions become one of the major concerns on the human respiratory system. Durão et al.$^6$ stated that the total or partial replacement of conventional fuels by alternative fuels participates in fulfilling emission regulations and reduces CO$_2$ emissions as well as achieves the consumption target of bioenergy in the transport sector. Considerable efforts are needed to reduce both PM and NO$_x$ emissions by developing

Received: June 21, 2022
Accepted: September 14, 2022
Published: October 13, 2022
the combustion systems of diesel engine. The mixture of the chemical species of nitrogen dioxide (NO\textsubscript{2}) and nitric oxide (NO) is from the NO\textsubscript{x} emissions, which is governed by the availability of oxygen and higher combustion temperatures\textsuperscript{7}.

The solid and liquid phases of PM are produced from the complex mixture of organic and inorganic compounds. Because of the nature of diesel fuel composition and the compression—ignition process, NO\textsubscript{x} and PM are considered the focus of researchers all over the world. However, the degree of improvement in controlling the formation of NO\textsubscript{x} and PM is still not very satisfactory in a diesel engine. Different techniques such as injection timings, high injection pressure, and alternative fuels have been incorporated to reduce the PM and NO\textsubscript{x}\textsuperscript{9,10}.

Previous studies\textsuperscript{11–13} discussed the influence of engine operating conditions (load, speed, and injection timings) on the performance of diesel engine and emissions. Manipulation in injection strategies is another option to enhance the fuel mixture as well as produce a low level of soot particulate, engine noise, and NO\textsubscript{x}\textsuperscript{14}.

It is proved that the advanced injection timing can also be a good approach to provide more local lean mixtures due to an increase in ignition delay.\textsuperscript{15} The ignition delay is affected by varying the fuel injection timing, which in turn has an effect on the combustion and exhaust emissions of a diesel engine.\textsuperscript{16} The combustion temperature and pressure increased when fuel injection started later inside the combustion chamber, which results in a decrease in ignition delay. Thus, the variation in injection timing has a significant effect on NO\textsubscript{x} emissions, brake-specific fuel consumption (BSFC), and brake thermal efficiency (BTE) due to the changing maximum temperature and pressure inside the engine cylinder.\textsuperscript{17} It is reported that the small nanoparticulate has a magnified effect on the environment and human health.\textsuperscript{18} Previous work stated that the PM consists of ash, soluble organic fraction (SOF) liquid PM, hydrocarbons, water, and sulfates (SO\textsubscript{x}). The availability of oxygen and high combustion temperatures in the combustion process enhance the reduction of PM formation.\textsuperscript{19} Some studies have shown that the total number and mean particle size are reduced from the combustion of biodiesel when compared to the combustion of diesel fuel.\textsuperscript{20–22} They found that the reductions in soot precursors and high cylinder pressure help in the suppression of soot formation and agglomeration.

There are many technologies that have been used to reduce the levels of exhaust emissions emitted from diesel engines. These technologies include the fuel pretreatment technology (mixing fuel with bio-oil, alcohols, etc.), purification technology inside the engine by developing the design of the combustion chamber,\textsuperscript{23} and exhaust after-treatment technology outside the engine.\textsuperscript{24} After-treatment high-performance systems such as diesel particulate filters (DPFs) have been linked with the engine to control the PM. DPF is a ceramic material usually made of cordierite or silicon carbide (SiC) that has thousands of parallel channels of square section with adjacent channels joined at the ends. Exhaust gases enter through these channels where the filter walls retain soot particles and prevent the exit of their emission to the atmosphere.\textsuperscript{25,26} Di Sarli et al.\textsuperscript{27} developed a soot-oxidizing PM catalyst with a high-performance filter made of silicon carbide (SiC) coated with a layer of enhanced CeO\textsubscript{2}. Metallic Ag and Cu were dispersed and distributed on the sample surfaces. Landi et al.\textsuperscript{28} numerically studied the effects of combined temperature and catalyst activity on the regeneration dynamics of a diesel particulate catalytic filter (DPF). Di Sarli et al.\textsuperscript{29} examined the effect of washing the filter with metric nanoparticles to improve the performance of diesel particulate filter (DPF) regeneration.

It is reported in previous work that PPCI (partially premixed compression ignition) combustion has presented favorable results in terms of PM and NO\textsubscript{x} emissions.\textsuperscript{30–32} To reduce NO\textsubscript{x}-soot emissions, the reactivity of fuel and air–fuel mixture formation should be controlled with low-temperature combustion. The engine PPCI mode has received substantial attention in the current time as mentioned in previous studies.\textsuperscript{33–35} Furthermore, the RCCI engine was developed by Kokjohn et al.\textsuperscript{36} through varying equivalence ratio stratification and the fuel reactivity inside the engine using high and low reactivity of fuels. The dual fuel-based PPCI engine has been introduced by Inagaki et al.,\textsuperscript{37} which extends the engine operating range over high operation conditions of engine load and reduces the charge dilution levels. The PPCI combustion improves the mixing between air and fuel, in which premixed combustion can occur in the combustion chamber without diffusion flame.\textsuperscript{38} The concept of PPCI can be achieved during the combination of high exhaust gas recirculation (EGR) levels and manipulation in the injection timing.\textsuperscript{39} Hountalas et al.\textsuperscript{40} reported that the poor combustion process can occur due to the reduced oxygen availability inside the cylinder under higher EGR temperature. It is documented that a low level of NO\textsubscript{x} emissions and smoke was found with the PPC strategy.\textsuperscript{41}

The use of alternative fuels in the diesel engine has been the focus of most research studies due to their clean burning, wide availability, and eco-friendliness.\textsuperscript{42} It is reported in prior works\textsuperscript{43–45} that the PM, CO, and HC reduced from the combustion of cleaner fuels. The BTE increased during the combustion of cleaner fuels such as biodiesel and B20 (butanol–diesel blends) compared with diesel fuel.\textsuperscript{46} Other works have reported that the combustion of biodiesel and butanol–diesel blends increases the NO\textsubscript{x} emissions.\textsuperscript{47,48} The NO\textsubscript{x} formation occurs due to the high initial temperature of flame surrounded by excess air. In numerous studies, it is reported that the PM concentration reduced from the combustion of different blends of biodiesel. In addition, they found that the oxygen content of alternative fuels plays a vital role in reducing the total concentration of PM.\textsuperscript{39–41} The fuel blends of gasoline–diesel, n-butanol–diesel, and gasoline–n-butanol–diesel were studied with different reactivity fuel blends.\textsuperscript{42,43} They found that droplet evaporation, spray atomization, and the mixing of fuel—air before the start of ignition were improved from these blends. Duraisamy et al.\textsuperscript{44} and Zheng et al.\textsuperscript{45} observed that the NO\textsubscript{x}-soot emissions reduced with a low heat release rate and high ignition delay from the combustion of methanol–diesel, diesel–n-butanol, diesel–gasoline, and diesel–gasoline–n-butanol blends. The effect of using blends of diesel–gasoline was studied by Zhang et al.,\textsuperscript{46} and the results were compared with diesel fuel in CI engines. The smoke, NO\textsubscript{x}, and particulate emissions significantly reduced from the combustion of the gasoline–diesel blend. It has been reported that the injection timing has a strong variation effect on the NO\textsubscript{x} emissions, BSFC, and BTE in the CI engine fueled with diesel fuel and alternative fuels.\textsuperscript{47,48} It is suggested that the combination of biodiesel and EGR is beneficial in reducing NO\textsubscript{x} and PM compared to the conventional diesel fuel.\textsuperscript{47,48} The use of 20% oxygenated fuel blend and 15% ratio of EGR helps in decreasing the NO\textsubscript{x} emission and soot particulate.\textsuperscript{49}
All the studies mentioned above used clean diesel (i.e., it has very ultralow-sulfur components) except for the works presented by Chaichan et al.\(^2\),\(^3\) which used high sulfur content in fuels (Iraqi fuel source). In these studies, the authors sought to reduce the damage of abundant sulfur by adding bioethanol,\(^\text{18}\) nano-alumina suspension,\(^\text{12}\) and biodiesel with hydrogen and massive ratios of EGR.\(^\text{18}\) Chaichan et al.\(^\text{50}\) have studied the effect of adding biodiesel to high-sulfur diesel on the exhaust emissions emitted from the engine during the start operating period of cold, hot, and extremely hot weather conditions. Ekaab et al.\(^\text{51}\) investigated the use of biokerosene instead of diesel to take advantage of lower sulfur content in Iraqi kerosene (2000 ppm). The addition of biodiesel fuel to the high-sulfur diesel leads to the reasonable reductions in most of pollutant emissions, and this reduction was clearer with increasing methyl ester portion in the fuel blend. These studies unanimously agreed on the great damage of abundant sulfur by the extracted sulfur, and both are not available in the mentioned countries. Sulfur compounds in the exhaust cause catalyst toxicity and render after-treatment systems useless.\(^\text{53}\) Therefore, it is important to change the composition of the fuel before use in the engine and the combustion mode to reduce the negative effects of exhaust emissions on health and the environment.

2. EXPERIMENTAL SETUP

2.1. Engine Setup and Equipment. The tests were carried out using a four-cylinder, direct injection, compression ignition, Fiat (TD 313) engine equipped with an EGR system as presented in Figure 1. The engine specifications are listed in Table 1. A pressure transducer type (Kistler type 6125A piezoelectric) was used to measure the pressure inside the cylinder, and the data of in-cylinder pressure were recorded through LabVIEW-based MATLAB software. The pressure data inside the cylinder are processed to reach the highest pressure and apparent heat release rate (AHRR). According to the work of Dhahad et al.,\(^\text{32}\) the rate of heat release was calculated in this study.

The EGR system was equipped with a diesel engine in this study as presented in Figure 1. Furthermore, the EGR valve located at the right corner of the engine was used to control the rates of EGR. To record the variation in the temperatures of engine oil, exhaust, and air, K-type thermocouples were calibrated and installed in different locations of engine parts. The concentrations of hydrocarbon (HC), nitrogen oxide (NO\(_x\)), carbon dioxide (CO\(_2\)), and carbon monoxide (CO) were measured using a Multigas mode 4880 emissions analyzer. A precision sound level meter linked with a microphone (type 4615) was used to measure the overall sound pressure. The level of smoke opacity was analyzed using a smoke meter (AVL-415). An AEROCET GT-521 (USA-made) was used to collect the particulate matter (PM) in the exhaust pipe. The SO\(_2\) and H\(_2\)S emissions were measured using G460 (Germany-made). The Central Organization for Standardization and Quality Control (COSQC) of Iraq has calibrated all equipment used during all tests. The EGR rate was calculated using the following equation:\(^\text{32}\)

$$\text{EGR(\%)} = \frac{\dot{m}_{\text{EGR}}}{\dot{m}_{\text{EGR}} + \dot{m}_a} \times 100$$

where \(\dot{m}_{\text{EGR}}\) is the mass flow rate of EGR, which is controlled by the EGR valve. Meanwhile, the mass flow rate of fresh air is \(\dot{m}_a\). Furthermore, a water valve was used to control the EGR temperature.

2.2. Fuel Preparation and Testing Conditions. In this study, diesel and gasoline blends were tested in the diesel engine. The specifications of diesel, gasoline, and the diesel–gasoline blend are listed in Table 2. The properties of these fuels are obtained from suppliers, calculations, and publications. Fuels were supplied by Al-Doura Refinery in Iraq. The gasoline and diesel fuel have high sulfur contents of 500 and 1000 ppm, respectively, which have an effect on the results of engine emissions.\(^\text{52}\) The fuel blends of diesel–gasoline were prepared by mixing 50% gasoline, 48% diesel, and 2% cetane number (CN) improver (type 2-ethylhexyl nitrate, also known

---

**Table 1. Engine Specifications**

| Specification                  | Value                                  |
|-------------------------------|----------------------------------------|
| Engine type                   | Fiat (TD 313)                          |
| Cylinder number               | four                                   |
| Stroke number                 | four                                   |
| Cooling system                | water circulation                      |
| Air system                    | naturally aspirated                    |
| Compression ratio             | 17:1                                   |
| Valve number/cylinder         | two                                    |
| Injection design              | direct injection                       |
| Plunger diameter              | 26 mm                                  |
| Nozzle hole number            | 10                                     |
| Nozzle hole diameter          | 0.48 mm                                |
| Cylinder bore                 | 100 mm                                 |
| Cylinder stroke               | 110 mm                                 |
| Connecting rod length         | 165 mm                                 |
| Spray angle                   | 160°                                   |
| Engine capacity               | 3.666 L                                |
| Rated power                   | 8.6 kW at 3000 rpm                     |
| Nozzle opening pressure       | 40 MPa                                 |

**Figure 1.** Schematic of the engine test and sampling points.
Four types of fuels were tested (diesel, GD30, GD40, and GD50) using a conventional diesel engine. Experiments were carried out by changing the engine load at a constant speed and then the engine speed at a constant load. Fuel consumption, torque, and power were recorded and measured, and the emitted pollutants were measured. The tests were repeated at least three times for each fuel to ensure repeatability.

Table 2. Physical and Chemical Properties of Gasoline and Diesel Fuels

| property                  | diesel | gasoline | GD30 | GD40 | GD50 |
|---------------------------|--------|----------|------|------|------|
| cetane number             | 51.8   | 17       | 42   | 38   | 35   |
| boiling point (°C)        | 369.7  | 79       | 290  | 260  | 225  |
| at 15 °C, fuel density (kg/m³) | 844.3  | 682.1    | 795.6 | 780  | 765  |
| fuel caloric value (MJ/kg) | 45.80  | 38.90    | 43.7 | 43   | 42.35|
| lower heat value (MJ/kg)  | 42.30  | 42.41    | 42.33 | 42.34| 42.35|
| flash and fire point (°C) | 2.87   | 0.44     | 2.127| 1.9  | 1.645|
| molecular weight (g/mole) | 210    | 104      | 179  | 168  | 148  |
| C% (w/w)                  | 87     | 86       | 86.7 | 86.6 | 86.5 |
| H% (w/w)                  | 12.93  | 15.10    | 13.6 | 13.8 | 14.015|
| S% (w/w)                  | 1−2.5  | 5 × 10⁻⁴ | 0.7−1.75 | 0.6−1.5 | 0.5−1.25|

Table 3. Experimental Accuracies of Equipment

| measuring equipment                  | accuracy % |
|--------------------------------------|------------|
| engine speed                         | ±0.98%     |
| engine torque                        | ±1.24%     |
| meter of fuel flow                   | ±0.50%     |
| thermocouples                        | ±0.04%     |
| sound pressure                       | ±0.70%     |
| meter of air flow                    | ±0.07%     |
| dynamometer                          | ±0.90%     |
| emission concentrations (NOₓ, CO, and HC) | ±0.02%     |
| concentration of PM                  | ±0.20%     |
| emission concentration (SO₂ and H₂S) | ±0.78%     |

3. RESULTS AND DISCUSSION

As iso-octyl nitrate; this blend is called GD50. The second blend was prepared by mixing 58% diesel with 40% gasoline and 2% CN improver; this blend is called GD40. The third blend was prepared by mixing 30% gasoline with 68% diesel and 2% CN improver; this blend is called GD30. The selection of this added percentage (2%) was made based on the results of previous studies. The addition of gasoline to the conventional fuel can result in a change in the main properties of the gasoline–diesel blend by reducing the cetane number and lowering the heat content, viscosity, and flash point. These changes will have an effect on the characteristics of combustion, properties of spray evaporation, and engine emissions. At the same time, GD blends have much lower sulfur content than diesel as the sulfur content decreased by 47.5%, 38%, and 28.5% for GD50, GD40 and GD30, respectively. This significant reduction in the sulfur content will have an important effect on the pollutants emitted.

The first test of fuels was carried out under variable engine load and fixed engine speed at 1500 rpm. The second test of fuels was carried out under variable engine speed and fixed load at 44 kN/m². The injection timing was kept constant at 5° before top dead center (bTDC) according to the previous publications. The engine operates with the gasoline–diesel blend on PPC mode. The rate of EGR was kept constant at 15% for diesel and the diesel–gasoline blend. The sources of error that could occur during the tests were indicated by calibrating the equipment used in this study. Therefore, the uncertainty was determined in this study. For all tests, the measurement accuracy of the experimental equipment is listed in Table 3.

3.1. Combustion Characteristics

Figure 2 shows the effect of various types of fuels tested with a fixed load (54.17 kN/m²) and speed (1500 rpm) on the in-cylinder pressure. Diesel fuel gives the highest maximum pressure value compared to GD blends, and this trend can occur due to two factors. First, the addition of gasoline leads to a lower calorific value than diesel fuel, which reduces the total calorific value of the mixture used. The second factor is the use of the PPC method with GD blend operation, which means adopting low burning temperatures inside the combustion chamber due to the circulation of large quantities of exhaust gas, which in turn reduces the maximum pressure value of the mixtures. Notably, the first factor is more effective, as the maximum pressure value decreases more with the increase in the proportion of gasoline in the mixture. In general, the less addition of gasoline to the mixture causes the in-cylinder pressure to be close to that for diesel despite the use of PPC mode. The heat release rate (AHRR) was obtained by processing in-cylinder pressure data using MATLAB software. The trend of AHRR confirms the cylinder compression results. For diesel, the greater release of heat causes an increase in the combustion chamber temperature, which improves the quality of combustion and leads to an increase in the rate of heat release (ROHR). As for the PPC-based GD mixtures, the ROHR values of GD30, GD40, and GD50 are always lower than that of diesel fuel. The low rate of energy released indicates lower burning temperatures due to work at lower combustion temperatures. Figure 2 shows that the rate of heat released for GD30 is higher than its counterparts even for diesel with crank angles from 5° to 10° bTDC. Perhaps, the maximum AHRR is

![Figure 2. Effect of different gasoline–diesel blends on in-cylinder pressure and ROHR.](https://doi.org/10.1021/acsomega.2c03878)
for diesel fuel especially at the top dead center (TDC). This result indicates that the injection timing must be altered according to the type of GD mixture used to achieve optimal heat release from the blend combustion.

3.2. BTE and BSFC. The influence of different GD blends on the BTE is shown in Figure 3 under variable conditions of engine loads and speeds. It can be noticed that the GD blends (GD30, GD40, and GD50) decrease the BTE under variable engine loads and speeds (Figure 3) compared with diesel fuel. This could be due to the poor vaporization, atomization, and combustion of GD blends. The reduction of mixture temperature occurred due to the effect of cooling EGR (15%), which leads to deterioration of the BTE in GD blends. In addition, the GD blends have lower calorific values compared to diesel fuel that resulted from the lower calorific value of gasoline. The diesel fuel experiments were carried out at fixed injection timing (IT) at 19° bTDC, which represents the optimum IT for diesel fuel. Meanwhile, GT blends’ IT was 50° bTDC, which is the closest to the optimum IT for the used GT blends. This IT change allows the engine to run normally.

Figure 4 shows that the BSFC reduced with medium engine load, while it increased with increasing engine load. Furthermore, the BSFC increased during the combustion of gasoline–diesel blends in comparison with regular diesel fuel. A higher calorific value of diesel fuel listed in Table 2 leads to the reduction of the BSFC compared to the GD blends. This trend of the BSFC was already reported in the prior works in which the BSFC increased with the combustion of fuels that have low calorific values compared to the diesel fuel. Furthermore, 4.68, 7.7, and 14.37% were increments from the combustion of GD30, GD40, and GD50, respectively, in comparison with diesel fuel combustion (Figure 4). The BSFC is linked to the injection timing, and the closer it is to the optimum injection timing, the lower the fuel consumption due to the improvement of atomization and evaporation. Also, the injection timing further away from the optimum injection timing leads to a fuel consumption increase. Therefore, running the engine at the optimum IT for each GD blend will enhance the combustion rate as well as shorten the combustion time and result in reducing BSFC and increasing BTE. Thanks to the cetane number improver used, it reduced the ignition delay period of the GD blends. Moving into the PPCI system needs to focus on IT controllability to always have optimal IT or near it at least.

3.3. Exhaust Gas Temperature (EGT). The influence of different GD blends with PPC mode on the exhaust gas temperatures under variable engine loads and speeds is shown in Figure 5. The temperatures recorded in the exhaust increased with high conditions of engine loads and speeds. Furthermore, it can be found that the GD30, GD40, and GD50 blend combustion reduces the EGT by 21.3, 33.44, and 40.43%, respectively, in comparison with diesel fuel for different engine operating conditions. These high temperature reduction rates are due to the lower calorific value of GT blends compared to diesel fuel and also the presence of high in-cylinder dilution represented by EGR. The reduction in the EGT from the combustion of GD blends may also explain the changes in emissions and PM later on. In the comparison of GD blends, it can be seen the EGT reduced with the high percentage of gasoline in the fuel blends (GD40 and GD50) compared to GD30 for variable engine loads and speeds (Figure 5). As a result, PPC mode is about running the engine at low burning temperatures.
3.4. NO\textsubscript{x} Emissions. Figure 6 shows the effect of GD blends on oxide of nitrogen (NO\textsubscript{x}) concentrations under variable engine loads and speeds with PPCI. In the combustion process, low-temperature zones and more local lean zones are an important factor for inhibiting NO\textsubscript{x} emission formation.\textsuperscript{2} The high engine load conditions produced high level concentrations of NO\textsubscript{x} emissions\textsuperscript{4} compared with low engine loads for diesel and GD blends (Figure 6a). This is due to the fact that the combustion region is surrounded by excess air, which leads to an increase in combustion temperature that enhances the formation of NO\textsubscript{x} emissions. In addition, the increased mass of fuel injected with high engine load allows higher flame temperature. It can be noticed that the GD blends reduce the NO\textsubscript{x} emissions more than the diesel fuel under variable engine loads. The evaporation of the fuel, better air−fuel mixture, and the presence of 15% EGR contribute to the reduction of the flame temperature, which leads to the promotion of the NO\textsubscript{x} emission formation. The lower calorific value of GD mixtures compared to diesel reduces the combustion temperature, which is reflected positively in reducing the NO\textsubscript{x} emission levels. According to the current results, the specifications of PPCI combustion directly affect the NO\textsubscript{x} reduction. The emitted NO\textsubscript{x} concentrations are a resultant of all these parameters. As a final result, the effect of the first factors (EGR addition) is greater than the effect of the last factor (GDs’ lower calorific values), so NO\textsubscript{x} levels decreased in PPCI combustion compared to diesel.

On the other hand, it is found that the high condition of engine speed reduces the NO\textsubscript{x} emissions in comparison with medium conditions of engine speeds for diesel fuel and GD blends as presented in Figure 6b. This may be due to the decrease in oxidation time from an increase in engine speed. The same trend of diesel and GD blends is obtained in Figure 6b under variable engine speeds. Furthermore, Figure 6 shows that the high addition of gasoline to the diesel fuel (GD50) was beneficial in reducing the NO\textsubscript{x} emissions when compared with medium and low addition of gasoline to diesel fuel for GD30 and GD40, respectively. It is observed that the NO\textsubscript{x} emissions decreased by 25.94, 50.9, and 84% from the combustion of GD30, GD40, and GD50, respectively, in comparison with the diesel fuel.

3.5. CO Emissions. The effect of different GD blends and PPC mode on carbon monoxide (CO) under different engine loads and speeds is given in Figure 7. It was obtained that the combustion of GD30, GD40, and GD50 blends produces higher CO content in the exhaust by 10.4, 21.69, and 40.4%, respectively, compared to the diesel fuel for different engine loads. Complete combustion of fuel before the start of the power stroke is the most important reason for reducing the formation of CO. However, since the injection timing (IT) used in the study is retarded late for the GD blends, part of the oxidation processes will take place in the power stroke during piston subsidence, and the temperature drops inside the combustion chamber. As a result, Figure 7 shows an increase in the CO concentrations of GD blends. The carbon−hydrogen percentage reduced from adding gasoline to the blend, which results in the reduction of CO concentration. Moreover, the lower combustion chamber temperature of GD blends enhances the higher concentrations of CO and HC.

3.6. HC Emissions. Figure 8 shows the effect of different GD blends and PPC mode on unburnt hydrocarbons (HCs) under different engine loads and speeds. The results show that the HC concentration was increased during the combustion of
GD30, GD40, and GD50 by 9.6, 27.04, and 40.02%, respectively, in comparison with diesel fuel under variable engine loads (Figure 8a). This is due to the low temperatures inside the combustion chamber from the EGR effect and lower heating value of GD blends. In addition, the fast travel of gasoline vapor spray could be another result of the increase in HC concentration from the combustion of GD blends. It can also be observed that the level of HC concentration decreased at medium engine speeds for all fuels tested as depicted in Figure 8b. In addition, both conditions of engine speeds (low and high) lead to the increase in HC concentrations for diesel and GD blends. This could be due to the reduction of combustion chamber temperature at low engine speeds in addition to the existence of EGR. At higher speeds, the reduction in sufficient time for oxidation reactions is the main reason for justifying the increase in HC levels. It seems that the low addition of gasoline to the diesel fuel GD30 leads to the decrease in HC concentrations compared to the high addition of gasoline GD40 and GD50 under different conditions of engine loads and speeds (Figure 8).

3.7. Engine Noise. Figure 9 shows the different levels of engine noise from the combustion of GD blends and diesel fuel with PPC mode under variable engine loads and speeds. The level of noise was found to decrease during the combustion of GD blends compared to the diesel fuel under different loads and speeds. This is due to the decline in the combustion pressure, combustion-induced mechanical noise, and combustion noise radiation. It is reported that the increase in excessive cylinder pressure can increase the engine noise. In addition, the noise level increased with increasing conditions of engine loads and also with the engine speeds. The engine noise level reduced with high addition of gasoline in the fuel blend. The combustion of GD30, GD40, and GD50 decreased the engine noise (Figure 9a).
noise by 2.3, 5.4, and 7.8%, respectively, compared to the diesel fuel as presented in Figure 8.

3.8. Particulate Matter (PM) Concentrations. The influence of GD blends and PPC mode on PM (concentration and number) under variable engine operating conditions is shown in Figure 10. It is clear that the PM concentrations reduced under the medium conditions of engine loads and speeds. As the engine runs at medium speed and loads, sufficient heat is generated in the combustion chamber to oxidize the fuel, and the necessary time is also available for oxidation, which results in reduced PM emitted. These results are in agreement with the previous work conducted by Khalilarya et al.59 Furthermore, the combustion of GD blends significantly reduced the PM concentration compared to the diesel fuels under variable loads and speeds (Figure 10). This may be due to the low sulfur content in GD mixtures and the low carbon–hydrogen ratio. In addition, the availability of suitable temperatures inside the combustion chamber and sufficient oxidation time results in the decrease in the agglomeration and formation of particulate. During all tests, it can be noticed that the average reduction values in PM were 32, 41.7, and 70.97% under variable engine loads (Figure 10a) and 30, 37.5, and 64.83% under variable engine speeds (Figure 10b) from the combustion of GD30, GD40, and GD50, respectively, in comparison with diesel fuel. For all GD blends, the maximum decrease in PM concentration was found during the combustion of GD50 by 24.6% compared to the GD30 combustion by 11.3% and GD40 by 8.6%. These results confirm the impact of reducing sulfur content in the fuel. Another reason is that the oxidation of polycyclic aromatic hydrocarbon (PAH) is reduced under the low-temperature flames, which in turn reduced the soot coagulation into the PM. Therefore, the formation rate of PM decreased during the combustion process and through the exhaust pipe. The combustion under high conditions of engine loads and speeds was accompanied by an increase in the PM owing to the increase in the collision of soot particles and soot agglomerate together during the combustion process as shown in Figure 10. In the case of medium engine conditions, the PM was smaller owing to the lower collisions between soot particles and soot agglomerate for all fuels tested. In addition, the sufficient oxidation time and suitable temperatures for oxidation reactions inside the combustion chamber also contribute to smaller PM. The above results confirm the need to use after-treatments with diesel particulate filters (DPFs)60,

The average particle diameter ($d_p$) of PM from GD blends and diesel fuel under different conditions of diesel engine (loads and speeds) is shown in Figure 11. The results show that the $d_p$ decreased with the combustion of GD blends compared with the combustion of diesel fuel. The decrease in the probability of collisions between soot particles tends to reduce the total $d_p$ under different engine operating conditions (Figure 11). These results on the $d_p$ are in agreement with previous work61 on the collision of soot particles. A comparison of GD blends showed that the $d_p$ increased from the combustion of GD50 by 26 nm compared with the combustion of GD40 by 26 nm and GD30 by 28 nm under high engine load as depicted in Figure 11a. In the case of high engine speed, it can be observed that the GD50 combustion reduced $d_p$ (27 nm) compared with the combustion of GD40 (28 nm) and GD30 (29 nm), as shown in Figure 11b.
3.9. Sulfur Dioxide (SO$_2$) Concentrations. Iraqi diesel fuel is considered a bad fuel because it contains a high percentage of sulfur (from 10,000 to 25,000 ppm), which is a high percentage. Figure 12 shows the sulfur dioxide concentrations emitted from the engine. It is noticed that these concentrations decrease with an increase in the percentage of gasoline in the mixture, and their lowest levels are at GD50. Iraqi gasoline contains a sulfur content of up to 500 ppm, which means that GD mixtures with a lower sulfur content emitted lower SO$_2$ concentrations. An engine running at low speeds and loads produces high concentrations of this pollutant, which are reduced more when working at medium loads and speeds. At low loads and speeds, the heat inside the combustion chamber will be minimal with the availability of adequate time for oxidation to rapidly react sulfur atoms. At medium loads and speeds, the temperature of the combustion chamber increases and the oxidation of all molecules is also improved. Therefore, part of the sulfur content is oxidized to form SO$_2$, while other parts enter into the formation of other compounds such as aromatics and PM. Therefore, SO$_2$ concentrations are reduced in this range. The engine working with high loads or high engine speeds generates great heat inside the combustion chamber, which contributes to higher oxidation of fuel. However, it requires larger quantities of fuel, which means greater concentrations of sulfur. Therefore, SO$_2$ concentrations increase under these conditions. The engine fueled with GD30, GD40 and GD50 blends results in a decrease in SO$_2$ pollutants by 35.75, 49.75, and 57.85%, respectively, compared to diesel fuel under variable loads and fixed engine speed operation. In contrast, the SO$_2$ pollutants reduced by 31.66, 45.64, and 52.90% during the combustion of GD30, GD40, and GD50 blends, respectively, in comparison with diesel combustion under constant loads and variable speeds of engine operation.

EGR was applied to reduce the temperature inside the combustion chamber by absorbing an essential part of it, but the effectiveness of sulfur molecules and their rapid reaction cause oxidation, which makes their concentrations clear in the exhaust gas. SO$_2$ reacts with water vapor in the exhaust to form sulfur acids that damage the exhaust system and reduce its life. Also, these concentrations cause toxicity and damage to catalysts. Therefore, reducing the fuel content of sulfur becomes necessary to improve and reduce pollutants emitted from the PPCI engine.

3.10. Hydrogen Sulfide (H$_2$S) Concentrations. Hydrogen sulfide is considered one of the gases dangerous to human health, as concentrations of 100 ppm and above pose a serious danger to humans if exposure to them lasts from 1 to 4 h. However, if concentrations of H$_2$S exceed 500 ppm, it would cause immediate loss of consciousness and sometimes rapid death. Figure 13 shows the concentrations of this pollutant in the engine exhaust for the fuels tested for both variable load (a) and variable speed (b) conditions. The results show that the H$_2$S concentrations in the exhaust mainly depend on the amount of fuel injected into the combustion chamber. H$_2$S concentrations increased with the increase in engine load or speed, as in these cases, more fuel is injected. Hydrogen reacts with sulfur quickly, which results in large concentrations of H$_2$S, as shown in Figure 13. The concentrations of this pollutant decrease by using GD mixtures at rates close to the decrease in sulfur concentrations in these mixtures. GD50 produces the lowest concentrations of H$_2$S under all tested operating conditions. The use of GD30, GD40, and GD50 blends results in reduced H$_2$S by 30.19, 40.05, and 50.12%,
respectively, in comparison with diesel fuel for variable loads and constant speeds of engine operation. In the case of constant loads and variable speeds of engine operation, \( \text{H}_2 \text{S} \) decreased by 32, 38.28, and 43.56% from GD30, GD40, and GD50 blends, respectively, compared to diesel. Although the results of \( \text{H}_2 \text{S} \) concentrations did not reach dangerous levels, these emissions in closed areas (such as tunnels and garages) may pose a great risk to health due to the accumulation of these concentrations and upon reaching critical levels.\(^{62,64}\)

From the above results, the use of GD50 by converting conventional diesel engines to operate with PPCI mode can be considered an important first stage in reducing exhaust pollutants. Certainly, the Iraqi state should work on improving aging oil refineries to produce ultralow-sulfur diesel fuel.

4. CONCLUSIONS

The influence of GD blends and PPCI mode of an engine on the NO\(_X\) emissions and PM concentrations in a CI diesel engine has been investigated. It can be concluded that the BTE and BSFC decreased by around 17% during the combustion of GD blends compared to the diesel fuel. An insignificant reduction in the BTE was found with increasing addition of gasoline to the diesel compared to the low addition of gasoline. The BSFC was found to be increased with GD50 by 14.37% and GD40 by 7.7% compared with GD30 by 4.68%. It was found that the addition of gasoline to the diesel fuel with PPCI mode led to a significant reduction of NO\(_X\) emissions and PM. A significant reduction of NO\(_X\) emissions was achieved during the combustion of GD50 by 84%, GD40 by 50.9%, and GD30 by 25.94% in comparison with diesel fuel. The decrease in the exhaust gas temperatures with GD blend combustion revealed that the NO\(_X\) emissions are lower. The addition of gasoline fuel to diesel with PPCI mode had a positive effect on reducing the NO\(_X\) emissions under variable engine conditions. The CO and HC emissions increased with high engine loads and speeds for all fuels studied, but a significant increase in HCs and CO was found during the combustion of GD blends. The experimental results demonstrated that the number and concentration of PM decreased at medium engine loads and speeds in comparison to low and high engine conditions for all fuels tested. Furthermore, the combustion of GD blends reduced the average number and concentration of PM by 42.3% than those emitted from diesel fuel. Moreover, the average particle diameter (\( d_p \)) of PM was lower during the combustion of GD blends compared to the diesel fuel. The reduction in the sulfur content of GD blends led to a noticeable decrease in SO\(_x\) and \( \text{H}_2 \text{S} \) by 57.85% and 50.12%, respectively, when the GD50 blend was used. It can be concluded that the gasoline–diesel blends can be a good solution to overcome the major constraints found with PPCI mode. This study reported that the use of GD blends led to a significant reduction of NO\(_X\) formation and PM with insignificant losses in the BTE. Thus, more studies are needed to improve the BTE while adding after-treatment systems to ensure the validity of such systems to work within the parameters of the Euro 6 standard.

**AUTHOR INFORMATION**

**Corresponding Authors**

Ahmed A. Al-Amiery — Mechanical Engineering Department, University of Technology-Iraq, Baghdad 00964, Iraq; Department of Chemical and Process Engineering, Faculty of Engineering and Built Environment, Universiti Kebangsaan Malaysia (UKM), Bangi 43600 Selangor, Malaysia; orcid.org/0000-0003-1033-4904; Email: dr.ahmed1975@ukm.edu.my

Wan Nor Roslam Wan Isahak — Department of Chemical and Process Engineering, Faculty of Engineering and Built Environment, Universiti Kebangsaan Malaysia (UKM), Bangi 43600 Selangor, Malaysia; orcid.org/0000-0002-1051-3120; Email: wannnoroslam@ukm.edu.my

**Authors**

Midqdam T. Chaichan — Energy and Renewable Energies Technology Center, University of Technology-Iraq, Baghdad 00964, Iraq

Hayder A. Dhahad — Mechanical Engineering Department, University of Technology-Iraq, Baghdad 00964, Iraq

Complete contact information is available at: https://pubs.acs.org/10.1021/acsomega.2c03878

**Notes**

The authors declare no competing financial interest.

**ACKNOWLEDGMENTS**

The authors acknowledge Universiti Kebangsaan Malaysia (UKM) for the support. Also, we gratefully acknowledge W.N.R.W.I. for his project (GUP-2020-012).

**NOMENCLATURE**

- BMEP=brake mean effective pressure
- BTE=brake thermal efficiency
- CA=crank angle
- CO=carbon monoxide
- DI=direct injection
- \( d_p \)=average particle diameter
- EGR=exhaust gas recirculation
- HCs=hydrocarbons
- LTC=low-temperature combustion
- NO\(_X\)=nitrogen oxides
- PPCI=partially premixed combustion
- PM=particulate matter
- TDC=top dead center

**REFERENCES**

(1) Kim, H. J.; Jo, S.; Kwon, S.; Lee, J. T.; Park, S. NO\(_X\) emission analysis according to after-treatment devices (SCR, LNT+ SCR, SDPF), and control strategies in Euro-6 light-duty diesel vehicles. Fuel 2022, 310, No. 122297.

(2) Chaichan, M. T. Combustion and emission characteristics of E85 and diesel blend in conventional diesel engine operating in PPCI mode. Thermal science and Engineering progress 2018, 7, 45–53.

(3) Su, J., May. Research on the Impact of Automobile Exhaust on Air Pollution. In 2022 International Conference on Urban Planning and Regional Economy (UPRE 2022); Atlantis Press, 2022, pp. 497–501.

(4) Fayad, M. A. Effect of renewable fuel and injection strategies on combustion characteristics and gaseous emissions in diesel engines. Energy Sources, Part A 2019, 1–11.

(5) Dhahad, H. A.; Chaichan, M. T.; Megaritis, T. Performance, regulated and unregulated exhaust emission of a stationary compression ignition engine fueled by water-ULSD emulsion. Energy 2019, 181, 1036–1050.

(6) Durão, L.; Costa, J.; Arantes, T.; Brito, F. P.; Martins, J.; Gonçalves, M. Performance and emissions of a spark ignition engine operated with gasoline supplemented with pyrogasoline and ethanol. Energies 2020, 13, 4671.

(7) Fayad, M. A.; Tsolakis, A.; Fernández-Rodriguez, D.; Herreros, J. M.; Martos, F. J.; Lapuerta, M. Manipulating modern diesel engine particulate emission characteristics through butanol fuel blending and...
fuel injection strategies for efficient diesel oxidation catalysts. *Applied Energy* **2017**, *190*, 490–500.

(8) Farhan, S. M.; Wang, P. Post-injection strategies for performance improvement and emissions reduction in DI diesel engines—A review. *Fuel Process. Technol.* **2022**, *228*, No. 107145.

(9) Fayad, M. A.; Tso lakis, A.; Martos, F. J. Influence of alternative fuels on combustion and characteristics of particulate matter morphology in a compression ignition diesel engine. *Renewable Energy* **2020**, *149*, 962–969.

(10) Geng, L.; Li, S.; Xiao, Y.; Xie, Y.; Chen, H.; Chen, X. Effects of injection timing and rail pressure on combustion characteristics and cyclic variations of a common rail DI engine fuelled with FT diesel synthesized from coal. *J. Energy Inst. Technol.* **2020**, *93*, 2148–2162.

(11) Uyumaz, A.; Aydoğan, B.; Yılmaz, E.; Solmaz, H.; Aksoy, F.; Mutlu, I.; Ipç, D.; Calam, A. Experimental investigation on the combustion, performance and exhaust emission characteristics of poppy oil biodiesel–diesel dual fuel combustion in a CI engine. *Fuel* **2020**, *280*, No. 118588.

(12) Chaichan, M. T.; Kadhum, A. A. H.; Al-Amiery, A. A. Novel technique for enhancement of diesel fuel: Impact of aqueous alumina nano-fluid on engine’s performance and emissions. *Case studies in thermal engineering* **2017**, *10*, 611–620.

(13) Wooldridge, M. S.; Singh, R.; Gutierrez, L. G.; Clancy, S. Survey of strategies to reduce cold-start particulate, CO, NOx, and hydrocarbon emissions from direct-injection spark-ignition engines. *International Journal of Engine Research* **2022**, *14680874211068576*, *14680874211068576*.

(14) Nayak, S. K.; Hoang, A. T.; Nižetić, S.; Nguyen, X. P.; Le, T. H. Effects of advanced injection timing and inducted gaseous fuel on performance, combustion and emission characteristics of a diesel engine operated in dual-fuel mode. *Fuel* **2022**, *310*, No. 122323.

(15) Hamza, N. H.; Ekaab, N. S.; Chaichan, M. T. Impact of using Iraqi biofuel–keresone blends on coarse and fine particulate matter emitted from compression ignition engines. *Alexandria Engineering Journal* **2020**, *59*, 1717–1724.

(16) How, H. G.; Masuki, H. H.; Kalam, M. A.; Teoh, Y. H. Influence of injection timing and split injection strategies on performance, emissions, and combustion characteristics of diesel engine fueled with biodiesel blended fuels. *Fuel* **2018**, *213*, 106–114.

(17) Fayad, M. A.; Al-Salih, H. A.; Dhadah, H. A.; Mohammed, F. M.; Al-Ogidi, B. R. Effect of post-injection and alternative fuels on combustion, emissions and soot nanoparticles characteristics in a common-rail direct injection diesel engine. *Energy Sources, Part A* **2021**, 1–15.

(18) Satar, I.; Isahak, W. N. R. W.; Salimon, J. Characterization of biodiesel from second generation gamma-irradiated Jatropha curcas. *Journal of the Taiwan Institute of Chemical Engineers* **2015**, *49*, 85–89.

(19) Chien, S.; Huang, Y.; Chuang, S.; Yang, H. Effects of biodiesel blending on particulate and polycyclic aromatic hydrocarbon emissions in nano/ultrafine/fine/coarse ranges from diesel engine. *Aerosol Air Qual. Res.* **2009**, *9*, 18–31.

(20) Fayad, M. A.; Herreros, J. M.; Martos, F. J.; Tsolakis, A. Role of alternative fuels on particulate matter (PM) characteristics and influence of the diesel oxidation catalyst. *Environ. Sci. Technol.* **2015**, *49*, 11967–11973.

(21) Yongsheng, G. Tail gas pollution from the vehicles and its control technology. *Environ. Sci. Survey* **2010**, *29*, 62–69.

(22) Piqiang, T.; Deyuan, W.; Diming, L.; Zhiyuan, H. Progress of control technologies on exhaust emissions for agricultural machinery. *Transactions of the Chinese Society for Agricultural Machinery* **2018**, *34*, 1–14.

(23) Lisi, L.; Landi, G.; Di Sarli, V. The issue of soot-catalyst contact in regeneration of catalytic diesel particulate filters: a critical review. *Catalysts* **2020**, *10*, 1307.

(24) Di Sarli, V.; Landi, G.; Di Benedetto, A.; Lisi, L. Synergies between ceria and metals (Ag or Cu) in catalytic diesel particulate filters: effect of the metal content and of the preparation method on the regeneration performance. *Top. Catal.* **2021**, *64*, 256–269.

(25) Landi, G.; Di Sarli, V.; Lisi, L. A numerical investigation of the combined effects of initial temperature and catalyst activity on the dynamics of soot combustion in a catalytic diesel particulate filter. *Top. Catal.* **2021**, *64*, 270–287.

(26) Di Sarli, V.; Landi, G.; Lisi, L.; Saliva, A.; Di Benedetto, A. Catalytic diesel particulate filters with highly dispersed ceria: Effect of the soot-catalyst contact on the regeneration performance. *Appl. Catal., B* **2016**, *197*, 116–124.

(27) Ma, C.; Song, E. Z.; Yao, C.; Long, Y.; Ding, S. L.; Xu, D.; Liu, Z. L. Multi-objective optimization of dual-fuel engine performance in PPC1 mode based on preference decision. *Fuel* **2022**, *312*, No. 122901.

(28) Fayad, M. A. Effect of fuel injection strategy on combustion performance and NOx/smoke trade-off under a range of operating conditions for a heavy-duty DI diesel engine. *SN Appl. Sci.* **2019**, *1*, 1–10.

(29) Hoang, A. T. Critical review on the characteristics of performance, combustion and emissions of PCCI engine controlled by early injection strategy based on narrow-angle direct injection (NADI). *Energy Sources, Part A* **2020**, 1–15.

(30) Kokjohn, S. L.; Hanson, R. M.; Splitter, D. A.; Reitz, R. D. Experiments and modeling of dual-fuel HCCI and PCCI combustion using in-cylinder fuel blending. *SAE Int. J. Engines* **2009**, *2*, 24–39.

(31) Inagaki, K.; Fuyuto, T.; Nishikawa, K.; Nakakita, K.; Sakata, I. Dual-fuel PCCI combustion controlled by in-cylinder stratification of ignitability. *SAE Technical Paper* (No. 2006-01-0028), 2006.

(32) Hountalas, D. T.; Mavropoulos, G. C.; Binder, K. B. Effect of exhaust gas recirculation (EGR) temperature for various EGR rates on heavy duty DI diesel engine performance and emissions. *Energy* **2008**, *33*, 272–283.

(33) Kumar, P.; Sandhu, S.S.; Singh, M.; Deep, A. Potential assessment of methanol to reduce the emission in LTC mode diesel engine. In *Methodol* Springer: Singapore, 2021, pp. 271–292.

(34) Kaewbuddee, C.; Sukjit, E.; Srisertpol, J.; Mathimklang, S.; Wathakit, K.; Klinkaew, N.; Liplap, P.; Arjharn, W. Evaluation of waste plastic oil-biodiesel blends as alternative fuels for diesel engines. *Energies* **2020**, *13*, 2823.

(35) Garcia, A.; Gil, A.; Monsalve-Serrano, J.; Sari, R. L. OMEEx-diesel blends as high reactivity fuel for ultra-low NOx and soot emissions in the dual-mode dual-fuel combustion strategy. *Fuel* **2020**, *275*, No. 117898.

(36) Dhadah, H. A.; Chaichan, M. T. The impact of adding nano-AI2O3 and nano-ZnO to Iraqi diesel fuel in terms of compression ignition engines’ performance and emitted pollutants. *Thermal Science and Engineering Progress* **2020**, *18*, No. 100535.

(37) Wang, S.; Karhicickeyan, V.; Sivakumar, E.; Lakshminikanad, M. Experimental investigation on pumpkin seed oil methyl ester blend in diesel engine with various injection pressure, injection timing and compression ratio. *Fuel* **2020**, *264*, No. 116868.

(38) Dhadah, H. A.; Fayad, M. A. Role of different antioxidants additions to renewable fuels on NOX emissions reduction and smoke number in direct injection diesel engine. *Fuel* **2020**, *279*, No. 118384.

(39) Jung, Y.; Hwang, J.; Bae, C. Assessment of particulate matter in exhaust gas for biodiesel and diesel under conventional and low temperature combustion in a compression ignition engine. *Fuel* **2016**, *165*, 413–424.

(40) Wei, L.; Cheung, C. S.; Ning, Z. Influence of waste cooking oil biodiesel on combustion, unregulated gaseous emissions and particulate emissions of a direct-injection diesel engine. *Energy* **2017**, *127*, 175–185.

(41) Man, X.; Cheung, C. S.; Ning, Z. Effect of diesel engine operating conditions on the particulate size, nanostructure and oxidation properties when using wasted cooking oil biodiesel. *Energy Procedia* **2015**, *66*, 37–40.

(42) Liu, H.; Wang, X.; Wu, Y.; Zhang, X.; Jin, C.; Zheng, Z. Effect of diesel/PODE/ethanol blends on combustion and emissions of a heavy duty diesel engine. *Fuel* **2019**, *257*, No. 116064.

(43) Zheng, Z.; Yue, L.; Liu, H.; Zhu, Y.; Zhong, X.; Yao, M. Effect of two-stage injection on combustion and emissions under high EGR
rate on a diesel engine by fueling blends of diesel/gasoline, diesel/n-butanol, diesel/gasoline/n-butanol and pure diesel. Energy Convers. Manage. 2015, 90, 1–11.

(44) Duraisamy, G.; Rangasamy, M.; Govindan, N. A comparative study on methanol/diesel and methanol/PODE dual fuel RCCI combustion in an automotive diesel engine. Renewable Energy 2020, 145, 542–556.

(45) Zhang, F.; Xu, H.; Zhang, J.; Tian, G.; Kalghatgi, G. Investigation into light duty dieseline fuelled partially-premixed compression ignition engine. SAE International Journal of Engines 2011, 4, 2124–2134.

(46) Appavu, P. Effect of injection timing on performance and emission characteristics of palm biodiesel and diesel blends. J. Oil Palm Res. 2018, 30, 674–681.

(47) Choi, M.; Mohiuddin, K.; Kim, N.; Park, S. Investigation of the effects of EGR rate, injection strategy and nozzle specification on engine performances and emissions of a single cylinder heavy duty diesel engine using the two color method. Appl. Therm. Eng. 2021, 193, No. 117036.

(48) Fayad, M. A. Investigating the influence of oxygenated fuel on particulate size distribution and NOx control in a common-rail diesel engine at rated EGR levels. Thermal Science and Engineering Progress 2020, 19, No. 100621.

(49) Saravanan, S. Effect of exhaust gas recirculation (EGR) on performance and emissions of a constant speed DI diesel engine fueled with pentanol/diesel blends. Fuel 2015, 160, 217–226.

(50) Chaichan, M.; Gaaz, T. S.; Al-Amiery, A.; Kadhum, A. A. Biodiesel blends startability and emissions during cold, warm and hot conditions. J. Nanofluids 2020, 9, 75–89.

(51) Zulkarnai, F. F.; Taib, N. M.; Mahmood, W. M. F. W.; Mansor, M. R. A. Combustion characteristics of diesel and ethanol fuel in reactivity controlled compression ignition engine. Journal of Advanced Research in Numerical Heat Transfer 2020, 2, 1–13.

(52) United Nation Environment Program. The sulphur campaign, available at: https://www.unenvironment.org/explore-topics/transport/what-we-do/partnership-clean-fuels-and-vehicles/sulphur-campaign.

(53) Wachter, P.; Gaber, C.; Raic, J.; Demuth, M.; Hochanauer, C. Experimental investigation on H2S and SO2 sulphur poisoning and regeneration of a commercially available Ni-catalyst during methane tri-reforming. Int. J. Hydrogen Energy 2021, 46, 3437–3452.

(54) Örs, I. Experimental investigation of the cetane improver and bioethanol addition for the use of waste cooking oil biodiesel as an alternative fuel in diesel engines. J. Braz. Soc. Mech. Sci. Eng. 2020, 42, 1–14.

(55) Simšek, S.; Samet, U. Analysis of the effects of cetane improver addition to diesel on engine performance and emissions. Int. J. Automot. Eng. Technol. 2021, 10, 26–32.

(56) Hu, J.; Chen, Z.; Yao, Y.; Shi, L.; Deng, K. Study on control-oriented emission predictions of PPCI diesel engine with two-stage fuel injection. Fuel 2022, 320, No. 123984.

(57) Alias, N. I.; Jayakumar, J. K.; Zain, S. M. Characterization of waste cooking oil for biodiesel. Jurnal Kejuruteraan 2018, 1, 79–83.

(58) Krishnamoorthi, M.; Malayalamurthi, R.; Shameer, P. M. RSM based optimization of performance and emission characteristics of DI compression ignition engine fuelled with diesel/aegle marmelos oil/diethyl ether blends at varying compression ratio, injection pressure and injection timing. Fuel 2018, 221, 283–297.

(59) Khalilarya, S.; Khatamnezhad, H.; Jafarmadar, S.; Oryani, H.; Pourfallah, M. Numerical investigation on the effect of injection timing on combustion and emissions in a di diesel engine at lowtemperature combustion conditions. Int. J. Eng. 2011, 24, 165–179.

(60) Di Sarli, V.; Di Benedetto, A. Operating map for regeneration of a catalytic diesel particulate filter. Ind. Eng. Chem. Res. 2016, 55, 11052–11061.

(61) Fayad, M. A.; Dhalahd, H. A. Effects of adding aluminum oxide nanoparticles to butanol-diesel blends on performance, particulate matter, and emission characteristics of diesel engine. Fuel 2021, 286, No. 119363.