Effect of fuel injection strategy on combustion performance and NO_x/smoke trade-off under a range of operating conditions for a heavy-duty DI diesel engine

Mohammed A. Fayad¹

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Abstract

The combustion process and exhaust emissions of a conventional diesel engine can be improved by manipulating the injection strategy (timing and pressure) without modification of the design. In this work, the influence of the injection strategy on the NO_x emissions and smoke level was investigated experimentally for a heavy-duty diesel engine operated using diesel fuel. Different injection timings and pressures were applied to produce a variety of engine-out emission levels over different engine operating conditions. The experimental results revealed that retarding the fuel injection timing enhanced the fuel economy by reducing the brake-specific fuel consumption (BSFC). In addition, the NO_x emissions were also reduced by retarding the injection timing at different engine speeds and loads. For the tested operating conditions, the NO_x emissions and BSFC were lower at low engine speed and high engine load, in particular at 1200 rpm and full load (100%), respectively. The results of the experimental work indicated that the brake thermal efficiency (BTE) increased with retarded injection timings at various engine speeds. Also, the BTE was higher at low engine speed (1800 rpm) and for different injection timings. Besides, the smoke level was improved for retarded injection timing and low engine speed. Lower exhaust smoke opacity was obtained at high injection pressure compared with low injection pressure for different engine test conditions. Use of the control engine operating conditions and high injection pressure enhanced the exhaust gas temperature and BSFC, but slightly increased the NO_x emissions.

Keywords Engine performance · Injection pressure · Injection timing · Operating conditions · Nitrogen oxides (NO_x) · Emissions · Diesel engine

Abbreviations

ET	Exhaust gas temperature (K)
P_{inj}	Fuel injection pressure (bar)
NO _x	Nitrogen oxides
CO	Carbon monoxide
HC	Hydrocarbon
BSFC	Brake-specific fuel consumption (g/kWh)
bTDC	Before top dead center
θ	Injection advance angle (°, before top dead center)
rpm	Revolutions per minute
N	Engine speed

1 Introduction

It is well known that nitrogen oxides (NO_x) are emitted due to the high combustion temperatures found in diesel engines. In recent years, NO_x emissions have become a concern and interest for researchers due to their toxic effect and the challenge of their reduction during diesel engine operation. Due to stringent emissions regulations, the search for different strategies to control smoke, total hydrocarbons (THC), and NO_x emissions in diesel engines has become an increasing focus [1–3]. It is reported that the injection timing has a significant effect on NO_x emissions and is thus considered to be an effective tool for their

✉ Mohammed A. Fayad, 11013@uotechnology.edu.iq | ¹Energy and Renewable Energies Technology Center, University of Technology-Iraq, Baghdad, Iraq.

control [4]. Stone [5] and Chen [6] studied the emission formation mechanisms and how retarded injection timing and exhaust gas recirculation affect NO_x formation. It has been documented that increasing the injection rate leads to a reduction in the brake-specific fuel consumption (BSFC) and increased NO_x emissions, while retarded injection timing increases the BSFC and reduces NO_x emissions [7, 8]. Robert [9] and How [10] reported that advanced injection timing and increased injection pressure can result in a lower level of engine-out emissions. In addition, they found that CO and CO_2 emissions were significantly reduced by advancing the fuel injection timing. In contrast, those researchers indicated that diesel engines produce low levels of smoke opacity and NO_x emissions when the fuel injection is retarded [11]. The effect of high fuel injection pressure and injection timing has been reported to reduce exhaust emissions from diesel engines. Previous experimental results studied the effect of retarding the fuel injection timing on the fuel economy and exhaust emissions of a diesel engine under different operating conditions [12]. It was found that retarding the injection timing contributed to reducing NO_x emissions but reduced fuel efficiency.

Numerous studies have reported that retarding the fuel injection timing increased the fuel economy penalty [10, 13]. Therefore, new strategies have been utilized in diesel engines to reduce the ignition delay, for example, higher compression ratio and higher injection pressure (to enhance the spray characteristics) [12]. Surveying the many studies reported in literature, the experimental study presented by Pickett et al. [14] showed that adjustment of the fuel injection pressure using high-pressure fuel injection equipment can improve the performance of a single-cylinder diesel engine. It was observed that increasing the injection pressure improved the combustion characteristics and reduced some gaseous emissions, but increased the noise level and NO_x emissions. Moreover, increasing the injection pressure can also make the fuel density distribution in the spray more homogeneous and increase the intensity of turbulence, resulting in improved fuel–air mixing [15–17]. Nehmer et al. [18] and Tow et al. [19] calculated the effect of the injection rate and multiple injections on the exhaust emissions of a diesel engine, concluding that pulsed injection could provide a means to reduce NO_x emissions through a controlled pressure rise. High fuel injection pressure is thus one of the requirements to achieve continuous improvements in exhaust gas emissions and smoke levels, also contributing to reduced engine noise [20].

Soot formation and oxidation are associated with the local oxygen availability and temperature in the combustion process [21]. Unmixed fuel prior to the start of combustion is likely to suffer from the combined effect

of lack of oxygen and high temperature later in the combustion cycle. Furthermore, fuel that is injected after the combustion process has started receives insufficient oxygen, hence most exhaust soot results from the second phase of burning [13, 22]. The effect of different operating conditions on the exhaust emissions and engine fuel economy has been investigated by many researchers [9, 12, 18]. The experimental work presented herein contributes to this field with a special emphasis on the effect of various fuel injection strategies (timings and pressures), having a positive effect on engine-out pollutants. The main aim of this study is to investigate the effect of different injection strategies on exhaust NO_x and smoke emissions and fuel economy at different operating conditions for a direct-injection (DI) heavy-duty diesel engine. The exhaust gas temperature for different fuel injection pressures and various engine speeds and loads is also investigated.

2 Experimental setup and materials

A schematic diagram of the heavy-duty (six-cylinder) direct-injection, water-cooled diesel engine and the instrumentation necessary for measuring the engine emissions and performance is shown in Fig. 1. The engine specifications and fuel properties are presented in Tables 1 and 2, respectively. A heat exchanger tower system was used to measure the engine coolant temperature. K-type thermocouples were used to monitor and measure all engine fluid temperatures. The research engine was supported by a rigid frame during testing and linked with a dynamometer to achieve steady operation without vibration. External loading was applied by using a Froude DRY-type hydraulic dynamometer and a cardan shaft with two universal joints. The dynamometer with a mechanical scale was used to measure the engine torque. The dynamometer is claimed to be accurate to within $\pm 0.025\%$ of nominal rating. The exhaust temperature was measured using a K-type thermocouple with a special multichannel amplifier. All engine operating conditions and temperatures were obtained using a computer-controlled data acquisition and recording system. The engine oil pressure and temperature, speed, standard engine test rig instrumentation, inlet and outlet water temperatures of the engine and dynamometer, and exhaust temperature were measured using conventional gages. An electrochemical gas analyzer was applied to measure the NO_x emissions in the exhaust, recording the measurement directly from the digital display screen. Furthermore, a Hartridge MK3b smoke meter was applied to measure the smoke opacity for different engine operating conditions.

Fig. 1 Experimental setup and measuring devices **Table 1** Engine specifications

Diesel engine parameter	Specification
Type	Six cylinder
Rated horsepower (hp)	505
Maximum torque	1810 ft-lb at 1100 rpm
Maximum speed	2200 rpm
Bore/stroke (mm)	150/170
Displacement (L)	12.8
Compression ratio	16:1

Table 2 Physical and chemical properties of diesel fuel

Property	Value
Molar weight (g)	148.3
Derived cetane number	50–55
Density at 15 °C (kg/m ³)	824
Specific gravity	0.83
Flammability in air (% by vol)	0
Stoichiometric air–fuel ratio	14.4
Latent heat of vaporization (kJ/kg)	241
Lower heating value (MJ/kg)	42.5
Upper heating value (MJ/kg)	45.1
Autoignition (K)	524
Carbon content (wt%)	86
Oxygen content (wt%)	0

3 Experimental results and discussion

3.1 Combustion performance

The effect of the fuel injection pressure on the average cylinder pressure and rate of heat release (ROHR) is shown as a function of crank angle degree (CAD) in Fig. 2. It can be seen that the in-cylinder combustion

pressure and rate of heat release (ROFR) increased with increasing fuel injection pressure. The main reason for this is the enhancement of the fuel mixture (air/fuel), which advances the start of combustion [23]. Furthermore, the faster and stronger vaporization process and faster combustion process with increasing fuel injection pressure could also increase both the cylinder pressure and ROHR, as depicted in Fig. 2. Significant effective work can be produced by increasing the fuel injection pressure, which could improve the brake thermal efficiency. High injection pressure leads to a fast and shorter combustion duration, increasing the rate of heat release.

3.2 Effect of fuel injection timing

The NO_x emissions can be controlled by manipulating the fuel injection timing [23]. Furthermore, any change in the fuel injection timing can significantly influence the ignition delay by injecting fuel before the start of combustion. This can alter the time and pattern of heat release, thereby affecting the maximum combustion temperature and pressure. In this experimental work, the fuel injection timing (θ) was varied from 32° to 26° before top dead center (bTDC). The NO_x emission levels in the exhaust pipe and the brake-specific fuel consumption (BSFC) of the diesel engine for different injection timings are shown in Fig. 3. Note that the concentration of NO_x emissions was reduced when retarding the injection timing (Fig. 3). This is due to the shorter delay period and less fuel injected before ignition. In addition, the lower peak pressure and combustion temperature lead to decreased NO_x emissions because a larger amount of fuel burns during the expansion stroke (later part). On the other hand, the brake-specific fuel consumption reduced when advancing the injection timing but increased with retarded fuel injection timings, as shown in Fig. 4. The main reason to justify this effect is that the reduced fuel delivery to the cylinder leads to a reduction in the BSFC. It is stated that a decrease of the ignition

Fig. 2 Average cylinder combustion pressure and rate of heat release (ROHR) for different fuel injection pressures

Fig. 3 Effect of fuel injection timing on NO_x emissions for different engine operating conditions

delay results in less fuel energy being injected during the combustion of the premixed phase. It is reported in literature that the BSFC is reduced by 6% when retarding the injection timing of an engine by 4° [24]. In contrast, the main effect increasing the BSFC is the lower calorific value,

which can lead to an increase in the fuel mass required to achieve the same output power, as stated by Lapuerta et al. [10, 25, 26] (Fig. 4). Moreover, it has been found that the BSFC increases with high engine speed for different engine loads [13]. This could be due to the increased brake

Fig. 4 Effect of fuel injection timing on brake-specific fuel consumption (BSFC) for different engine operating conditions

Fig. 5 Effect of fuel injection timing on brake thermal efficiency (BTE) at full load and different engine speeds

thermal efficiency resulting from the shift of the expansion process.

Investigation of the effect of changing the start of injection on engine efficiency revealed that retarding the injection timing towards top dead center led to a minor improvement in thermal efficiency [27]. Figure 5 reveals

that the brake thermal efficiency (BTE) increased when retarding the fuel injection for different engine speeds. It was reported by Suryawanshi et al. [27] that the thermal efficiency improved when retarding the injection timing (by a CAD of 4°). According to the results, the trend of the BTE was exactly reverse that of the BSFC during the experiment [12]. Furthermore, Fig. 5 reveals that the BTE was higher at low engine speeds for different injection timings. This is due to the increase in the compression ratio and fuel injection at higher temperature (better air/fuel mixing) [28]. Another reason could be due to the combination of the mass flow rate and low volatility, resulting in an increase in the BTE. The better fuel combustion and available residence time for mixing air and fuel (complete combustion) helps to increase the BTE at low engine speed.

3.3 Effect of fuel injection strategy on smoke level

The effect of the fuel injection timing on the smoke level for different engine loads and speeds is shown in Fig. 6a, b. Smoke formation can occur for retarded injection timing, which in turn reduces the ignition delay. The ignition delay

Fig. 6 Effect of fuel injection timing on smoke level for **a** full load and different engine speeds and **b** $N = 1800$ rpm and different loads

increases when advancing the start of fuel injection as more fuel is injected before ignition, which leads to higher temperatures in the combustion cycle (faster combustion and better mixing) [29]. Accordingly, the smoke level reduced with retarded compared with advanced injection timing, as shown in Fig. 6. This is due to the large amount of evaporated fuel that accumulates for advanced injection timing, which results in a longer ignition delay and thus a rapid burning rate [30, 31]. Note that retarding the fuel injection timing leads to a slight reduction in the average in-cylinder combustion pressure. It is thought that this could be due to the insufficient time available for proper mixing between air and fuel (slow burning) (Fig. 6). It is clear from the results presented in Fig. 6 that the smoke level increased at high engine speeds and full load (100%).

Figure 7a, b shows the effect of different injection pressures on the smoke level produced by combustion of diesel fuel. Partial reaction of carbon and unburned

hydrocarbons in the liquid fuel result in smoke formation. It can be observed in Fig. 7 that the smoke level was significantly reduced by increasing the fuel injection pressure due to the promotion of fuel–air mixing and decreased residence time for smoke opacity growth. Furthermore, note that high fuel injection pressure resulted in improvements in terms of particulate matter (PM) reduction, engine emissions, and fuel consumption economy [28]. It can be observed that the smoke level was evidently higher at high engine operating conditions (speed and load), especially for low fuel injection pressure. Note that the smoke level decreased by about 52% when increasing the fuel injection pressure from 200 to 240 bar (Fig. 7a, b). The main reason for this is that the high injection pressure inhibits particle formation and smoke opacity by offering more oxidants such as OH radicals.

Fig. 7 Effect of fuel injection pressure on smoke level for **a** full load and different engine speeds and **b** $N = 1800$ rpm and different loads

3.4 Effects of fuel injection pressure

Experiments were also performed to analyze the effect of the fuel injection pressure on the brake-specific fuel consumption (BSFC), exhaust temperature (ET), and NO_x emissions for different engine speeds and loads (Fig. 8a–d). Note that the BSFC reduced with increasing injection pressure for different engine speeds and loads (Fig. 8). This is due to the increased spray pressure and faster time to mixing (air/fuel), thus reducing the quantity of fuel for combustion. Furthermore, the greater energy provided by high injection pressures to

break up more viscous fuels into smaller droplets with faster evaporation leads to faster combustion. Moreover, higher injection pressure leads to faster ignition and earlier start of combustion, which in turn produces high pressures and temperatures (Fig. 2) in the combustion cycle. Figure 8 shows that the exhaust temperature (ET) increased with increasing fuel injection pressure for different engine operating conditions [32]. This may be related to the combustion temperature, as increasing the injection pressure leads to quicker combustion with high in-cylinder temperatures and eventually higher NO_x emissions. Another reason is the smaller droplet

Fig. 8 Effect of fuel injection pressure on BSFC, ET, and NO_x at different engine speeds for load of a 25%, b 50%, c 75% and d 100%

Fig. 8 (continued)

size distribution in the combustion cycle, which could enhance the fuel–air mixing, resulting in smoother combustion at high temperature. In addition, faster combustion with high injection pressure provides a short time for hot gases to expand and avoid engine cooldown before opening the exhaust valve, leading to increased exhaust temperatures. It can be seen that the exhaust temperature increased with higher engine speed and loads over different injection pressures (Fig. 8). This is due to the high pressure of the injected fuel, which increases the engine load and decreases the time period

to increase the engine speed, hence generating extra heat in the combustion cycle. The increase in the exhaust temperature has a twofold effect, firstly enhancing the oxidation of emitted gases along the exhaust pipe and secondly improving the performance of the aftertreatment system due to the higher temperature. Meanwhile, the level of NO_x emissions increased with increasing fuel injection pressure for different engine speeds (Fig. 8). Furthermore, the engine produced a high level of NO_x emissions at full compared with low engine load over different fuel injection pressures. This reduction could

be due to many reasons, for example, a high local combustion temperature produced by the high engine load, advancing the start of combustion [21, 33]. It is also documented that increasing the ignition delay and the combustion phase leads to an increase in the NO_x emissions [34].

4 Conclusions

The effects of different injection strategies (timing and pressure) on the combustion, nitrogen oxide (NO_x) emissions, brake-specific fuel consumption, brake thermal efficiency, and smoke level were investigated experimentally over different engine operating conditions for diesel fuel. The combustion analysis showed that increasing the fuel injection pressure contributed to an enhancement in the average cylinder combustion pressure and rate of heat release (ROHR). It can be concluded that the NO_x emissions reduced for retarded injection timings. This can be considered to be a good way to control NO_x emissions without depending on aftertreatment systems. Furthermore, it was observed that the BSFC was reduced when retarding the fuel injection timing. Lower NO_x emissions and low BSFC level were observed at low engine speed (1200 rpm). The results reveal that the brake thermal efficiency increased when retarding the fuel injection timing. For retarded fuel injection timings, the smoke level produced by the combustion of diesel fuel was reduced for different engine speeds and loads. In addition, use of a high injection pressure of 240 bar significantly reduced the smoke level by about 52%. The effects of the injection pressure on the brake-specific fuel consumption (BSFC), exhaust temperature (ET), and NO_x emissions were also investigated. It is important to mention that the BSFC was reduced when increasing the injection pressure, although the exhaust temperature and NO_x emissions were increased for different engine operating conditions (speeds and loads). The results of this study could generate research ideas regarding the interaction between injection strategies and engine performance. It can be concluded that increasing the injection pressure and advancing the injection timing improved the combustion performance and smoke level when operating with neat diesel fuel.

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Compliance with ethical standards

Conflict of interest The author declares that he has no conflicts of interest.

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