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An Experimental Investigation of the Effects of Diesel Fuel Injection Characteristics in a Heavy-Duty Direct Injection (HDDI) Diesel Engine

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Abstract: This experimental research aims to investigate the simultaneous effects of fuel injection characteristics on the combustion process in the D87 heavy-duty direct injection diesel engine. In this study, effects of 36 various injection strategies such as spraying pressure (1000, 1200, and 1400 bar), injection timing (6, 8, 10, and 12 CA BTDC), and fuel quantity (45, 90, 120, and 150 mm^3 per cycle) on combustion characteristics (MPPP and EGT), emissions formation (NOx and soot), and engine performance (brake power and BSFC) were explored. Results showed that increasing spraying pressure and quantity simultaneous with advancing fuel injection timing led to the increment of both MPPP and EGT and as a result, improvement of BSFC and brake power. However, due to lower AFR, higher combustion temperature, and shorter ignition delay period, both soot and NOx increased, which considered as a disadvantage of using this fuel injection strategy for the D87 diesel engine. In addition to that, for low fuel quantity per cycle (e.g., 45 mm^3) due to shorter spraying duration, fuel injection timing and pressure have a great impact on engine performance because of determining the time of combustion phase and energy loss per cycle.

keywords: Heavy-Duty Diesel Engine, Injection Pressure, Injection Timing, Air-Fuel Ratio, Emissions

1. Introduction

Decrement of oil resources and increase in environmental pollutant emissions have led to an increase in the cost of non-renewable fuel resources, as well as more stringent emission regulations by environmental organizations for using vehicles or any power generators equipped with internal combustion engines (Mobasheri, Seddiq, & Peng, 2018; Yuan et al., 2018). On the other hand, a dramatic increase in the population also has led to a sharp increase in fuel consumption due to the growth of the number of vehicles. Following that, the number of pollutant emissions produced by the IC engines of these vehicles significantly affected the environmental conditions (Christodoulou & Megaritis, 2013). By comparing diesel engines with spark ignition and gas engines, they have more durability and stability, lower fuel consumption, higher thermal efficiency, as well as low CO and CO_2 emissions (Hossain, Nabi, & Brown, 2019).

Over the past several years, in order to reduce the level of exhaust gas emissions such as NOx and soot, and improve the efficiency of CI diesel engines, extensive numerical and experimental research conducted by many researchers from universities and research centers (Raman et al., 2019; E et al., 2019; Yusri et al., 2019; Huang et al., 2019; Nabi et al., 2019; Killol et al., 2019). The purpose of these efforts was to make easy and possible use of CI diesel engine in a wide range of applications including on-road and stationary despite the strict environmental regulations and various types of restrictions. These researches include exploring the different solutions to improve both performance and emissions level of CI engines simultaneously. Increasing injection pressure (Wang et al., 2019; Jia, Yu, & Li, 2017), different spray cone angle (Shu et al., 2019; Payri et al., 2018), changing in fuel injection timing (Chen et al., 2018; Park, Kim, & Lee, 2018), and other

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effective methods are mentioned solutions that their effects on the combustion process of diesel engines were discussed in detail by many researchers.

In CI engines equipped with a direct fuel injection system, fuel spray timing significantly controls the combustion phase, which determines the level of the performance and amounts of exhaust gas emissions (Wang et al., 2015). In an experimental study, Wei et al. examined the influence of fuel direct injection timing on the performance and amount of emissions formation in a heavy-duty diesel-methanol CI engine (Wei et al., 2016). The results of their study have shown that by postponing the fuel injection timing, ignition delay period has prolonged, and the duration of combustion has not changed at the beginning but then slightly shortened. Also, the maximum point of in-cylinder pressure and temperature has decreased by delaying the time of fuel injection. They have reported that by retarding the diesel fuel injection timing, UHC emissions initially increased then decreased, but CO increased for all injection timings. In their experimental research paper, Guerry et al. studied the impacts of diesel injection timing on the performance and exhaust gas emissions in a DI diesel engine (Guerry et al., 2016). They conducted their study in 1500 RPM engine speed and a constant DI pressure of 500 bar. Their results indicated that advancing direct fuel injection timing has led to a more extended ignition delay period. In addition, the amount of NOx emissions have increased, and soot was reported to be insignificant for all injection timings. They have shown a considerable increase in the level of both CO and UHC by delaying diesel fuel injection timing near TDC point. The minimum amounts of CO and UHC emissions have been observed for 50 CA BTDC injection timing case. Benajes et al. explored the influence of direct fuel injection timing on the combustion process of reactivity controlled CI engine (Benajes et al., 2015). Their results showed that the formation of NOx emissions is proportional to the combustion temperature. Also, the timing of the fuel injection can lead to the combustion phase approaching near TDC point and increases the NOx level. They also reported that at medium and high load engine operation conditions, injection timing had slight effects on CO and UHC emissions but postponing the fuel injection timing led to the increment of both CO and UHC emissions.

Another specification of fuel injection in CI diesel engines is spraying pressure that directly affects the combustion by determining the quality of air-fuel mixing and oxidation process. Numerous computational and empirical studies have been conducted to investigate the impacts of injection pressure on the combustion process in DI diesel engines. According to the experimental research by Liu et al., increasing injection pressure led to shorter combustion duration and higher in-cylinder maximum pressure and heat release rate (Liu, Yao A., & Yao C., 2015). Also, combustion phase approached near TDC point. They reported that BSFC decreased and both NOx and soot emissions reduced by increasing diesel fuel injection pressure. In another experimental paper, Nanthagopal et al. investigated the effects of increasing fuel injection pressure on performance, amounts of emissions formation, and combustion characteristics in a DICI engine (Nanthagopal, Ashok, & Raj, 2016). They have indicated that increasing fuel injection pressure led to a significant improvement of BSFC and also, reduction of exhaust gas emissions such as CO, UHC, and soot. However, NOx emissions increased for higher injection pressures compared to the baseline case.

According to the above literature, which separate effects of fuel injection characteristics have been discussed, injection pressure and timing has considerable impacts on the combustion process of DI diesel engines. For this reason, in this experimental study that conducted on a 12 cylinder heavy-duty diesel engine, simultaneous effects of fuel injection characteristics such as pressure, timing, and quantity on the combustion process, amounts of exhaust gas emissions, and engine performance have been investigated.

2. Experimental Setup

This experimental study was conducted on a 12-cylinder heavy-duty diesel engine with the commercial name of D87. This engine was designed, build, and developed by Technomot Ltd- An Engine Technology Company in England under the inspection of Iran heavy Diesel Engine Manufacturing Company from 2004 to 2011. Table 1 reports some of the engine specifications. Also, Fig. (1) shows the schematic view of the D87 engine located in the test room.

To record and measure the results and functional characteristics of the test engine, suitable instruments were used which their model name, accuracy, and operating range can be found in Table 2.

EN-590 commercially available heavy diesel fuel used for this study and its specifications can be found in Table 3.

Table 1. Engine Specifications

Engine Type	Heavy-Duty, Water-cooled
Engine Aspiration	Turbo-Charged
Number of Cylinders	12
Bore (mm)	150
Stroke (mm)	180
Engine Displacement (L)	38.1
Compression ratio(-)	15.0:1
Fuel Injection System	Common rail Direct Injection
Injector Holder	HEINZMANN
Injector Nozzle Number	8
Nozzle Orifice Diameter (mm)	0.25
Rated Power (kW)	1000
Rated Speed (RPM)	1500

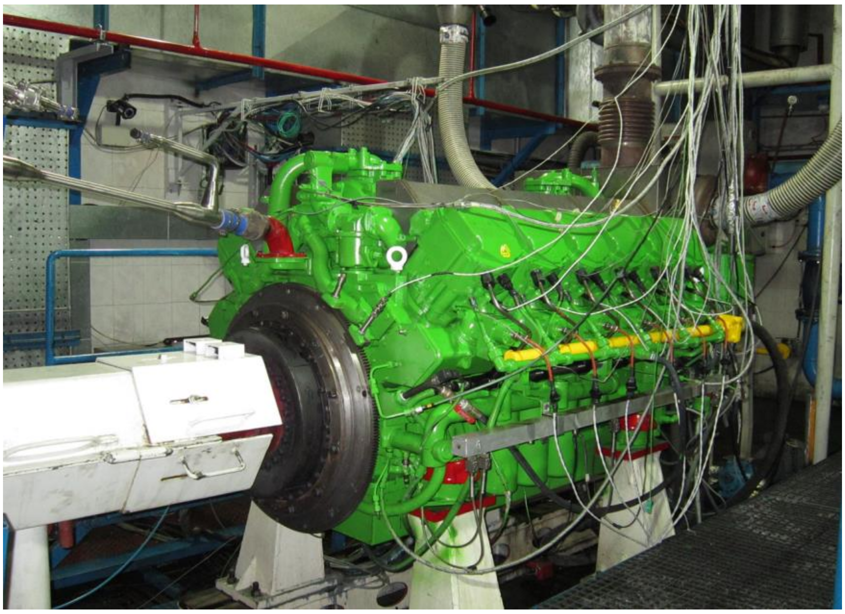

Figure 1. D87 Diesel engine in the test room

Table 2. Measuring Instruments Specification

Device	Model Name	Accuracy	Operating Range
Fuel consumption meter	FMS-3000	± 0.03 gr	0 – 200 kg/hr
Exhaust gas emission analyzer	Horiba Mexa 7170	-	NOx: 0 – 5000 ppm
Smoke meter	AVL 415s	0.02 mg/m³	0 – 100 mg/m³
Exhaust gas temperature	K-Type Thermocouple	2.2 ⁰C	-200 – 1300 ⁰C
Cylinder pressure	KISTLER-2853	-	0 – 250 bar

Table 3. Heavy Diesel Fuel Specifications

DIN-EN-590 (EU IV) by IPCO		
Property	**Standard No.**	**Value**
Chemical Formula	-	$C_nH_{1.8n}$
Density (kg/m³) @ 15 ⁰C	ISIRI-197	820 - 845
Cetane No. (-)	ASTM-D-613	>51
Cetane Index (-)	IP-380/EN-ISO-4264	>46
Viscosity (mm²/s) @ 40 ⁰C	ISIRI - 340	2.00 – 4.50
Flash Point (⁰C)	ISIRI-1175	>55
Sulphur Content (mg/kg)	ASTM-D-5453	<50
Carbon residue (%m/m)	ASTM-D-4530	0.3
Water Content (mg/kg)	ISIRI-154	<200
Ash (%m/m)	ISIRI-2940	<0.01
Lower Heating Value (kJ/kg)	(Soberanis & Fernandez, 2010)	42500
Flame Velocity (m/s)		0.3

Combustion Air Handling Units (CAHU) was used for supplying the required air for D87 engine operation. The purpose of using this system is to applying specific weather conditions to allow development tests and engine upgrades based on the geographical location of the D87 engine application. The operational characteristics of the air conditioning system (CAHU) and its schematic view are shown in Table 4 and Fig. (2), respectively.

Table 4. CAHU Operatitional Specifications

Air Flow Rate (kg/hr)	5800
Air Temperature (^{0}C)	23 - 28
Relative Humidity @ 25 ^{0}C (%)	40 - 60

3. Methodology

The primary purpose of building the D87 engine with a range of 500 kW to 1000 kW output power, was to be used for the railroad and marine transportation applications. Lots of development, emission, and performance tests were conducted on the D87 diesel engine by Technomot Company, and obtained results were sent to Iran heavy Diesel Engine Manufacturing Company for further inspections. Part of the tests were devoted to exploring the influence of fuel injection characteristics in the D87 diesel engine. For this reason, the authors of this research decided to present the results of this series of tests as a technical paper.

Thirty-six various injection strategies, according to Technomot recommendations, were tested on the D87 diesel engine. The purpose of the experimental tests was to investigate the simultaneous effects of fuel injection timing, spraying pressure and quantity on the combustion characteristics (Maximum in-cylinder pressure and exhaust gas temperature), amounts of emissions formation (NOx and soot), and engine performance (Indicated power and BSFC). Table 5 presents the conditions of the experimental tests for laboratory engine.

In order to record the obtained results from conducting fuel injection strategies on the D87 diesel engine, all measurements were made after the engine had reached a steady-state and operated for about 300 seconds continuously. In addition to that, it must be mentioned that based on the progress report from Technomot, some tests results were eliminated due to violating EURO three emissions regulation. Also, regarding emissions tests, only results of NOx and soot emissions were available for presenting in this experimental research paper.

Figure 2. Air conditioning system in the engine test room

Table 5. Experimental tests conditions for the D87 Diesel Engine

Engine test room air pressure (bar)	1.0
Engine test room air temperature (^{0}C)	25
Relative humidity of engine test room (%)	50
Engine cooling water temperature (^{0}C)	50
Engine lubricating oil temperature (^{0}C)	60
Intake air charge pressure (bar)	Variable from 1 to 1.7
Intake air charge temperature (^{0}C)	Variable from 40 to 55
Engine speed (RPM)	800
EGR rate (%)	0
Injection timing (CA BTDC)	12 – 6 (2 CA steps)
spraying pressure (bar)	1000 – 1400 (200 bar steps)
Fuel quantity (mm^3 per cycle)	45, 90, 120, and 150

4. Results and Discussion

In CIDI engines, the combustion process consists of two distinct phases: ignition delay and heat release period (Ramos, 1989). In-cylinder pressure, temperature, engine speed, and also the chemical properties of the consumed fuel are the factors that influence the duration of the ignition delay period. Furthermore, the heat release period has two modes: premixed and diffusive combustion (Ramos, 1989). For premixed combustion mode, the fuel is initially evaporated, then mixed with in-cylinder air (accumulation) and finally, the auto-ignition process proceeds. However, in diffusive combustion air-fuel mixing and auto-ignition process coinciding. Longer ignition delay period led to more fuel evaporated and mixed with air, and as a result, more fuel is burnt in premixed combustion mode. In other words, during ID period, a large portion of evaporated fuel auto-ignites at once that lead to considerable high pressure and temperature rise rate during premixed combustion mode. On the contrary, shorter ignition delay period due to less time available for air-fuel accumulation led to a large portion of injected fuel burns in diffusive combustion mode. Thus, compared to premixed combustion, less portion of evaporated fuel auto-ignites at once and as a result, lower pressure and temperature rise rate accruing by diffusive combustion.

Fig. (3) reports the simultaneous effects of fuel injection timing, spraying pressure, and quantity on the in-cylinder Maximum Pressure Peak Point.

As illustrated in Fig. (3), advancing fuel injection timing led to higher MPPP. In other words, by advancing the fuel injection timing, due to lower in-cylinder pressure and temperature compared with late injection timings, the ignition delay period has prolonged, and more fuel evaporated and accumulated. Thus, most of the air-fuel mixture burned in premixed combustion mode and resulted in higher MPPP. Also, based on the results indicated in Fig. (3), postponing the diesel fuel injection timing has decreased the in-cylinder MPPP. Due to the type of movement of the combustion chamber during the compression stroke, in-cylinder pressure and temperature are rising gradually, and by retarding the injection timing, fuel sprayed in regions with higher pressure and temperature compared to early ITs. Thus, the ignition delay period became shorter and led to a less air-fuel mixture accumulated. For this reason, a large portion of evaporated fuel burns in diffusive combustion and as can be seen in Fig. (3), postponing fuel injection timing resulted in lower MPPP.

As illustrated in Fig. (3), increasing fuel injection pressure led to the increment of in-cylinder MPPP. As the spraying pressure increases, fuel injection duration becomes shorter and leads to a shorter combustion duration. In addition to that, shorter injection duration can lead to the faster flame velocity and following that, higher heat release rate. Thus, according to Fig. (3), increasing fuel injection pressure resulted in increment of MPPP due to higher pressure and temperature rise rate caused by shorter combustion duration of the air-fuel mixture. Furthermore, as can be seen in Fig. (3), increasing the amount of fuel injection per cycle led to higher MPPP. By increasing the injection quantity, more fuel burns in each cycle and leads to higher heat release rate due to the burning of much more evaporated air-fuel mixture inside the combustion chamber.

Based on the presented results in Fig. (3), simultaneous increasing in spraying pressure, fuel quantity, and advancing injection timing, led to a significant increase in MPPP. It can be concluded that, due to more evaporated fuel burned in premixed combustion during a shorter period (combustion duration), MPPP considerably increased due to higher pressure, temperature, and heat release rise rate caused by enhanced air-fuel mixture and oxidation process.

Fig. (4) shows the simultaneous impacts of fuel injection timing, spraying pressure, and quantity on exhaust gas temperature.

As can be seen in Fig. (4), by increasing fuel injection quantity in each cycle, exhaust gas temperature considerably has increased. As mentioned earlier, by addition of fuel quantity, more heat released by the combustion of the air-fuel mixture, and as a result, the temperature of exhaust gas has increased. Moreover, by increasing fuel injection pressure for 45 and 90 mm^3 FIQ, exhaust gas temperature increased due to higher combustion temperature. However, as reported in Fig. (4), for 120 and 150 mm^3 FIQ, injection pressure has no significant impact on the EGT.

In Fig. (4), the results of the influence of fuel injection timing on the EGT are presented. As illustrated in Fig. 4, by advancing fuel injection timing for 45 mm^3 FIQ, EGT initially increased (For 1200 and 1400 bar spraying pressure) and then decreased. Also, for 90 mm^3 FIQ, advancing the injection timing led to a reduction of EGT from the beginning. However, there were no considerable impacts on the EGT by changing the injection timing for 120 and 150 mm^3 FIQ.

It can be concluded that for lower FIQ (e.g., 45 and 90 mm^3) diesel fuel spraying pressure and its injection timing has significant impacts on the combustion phase. Appropriate fuel spraying pressure and injection timing lead to combustion phase approach near TDC point and less energy loss per cycle. In other words, by advancing fuel injection timing for 45 and 90 mm^3 FIQ, the combustion phase occurs earlier and resulting in a more energy loss per cycle during the compression stroke. Thus, EGT has decreased. However, for 120 and 150 mm^3 FIQ, fuel injection timing, and spraying pressure have no considerable impacts on EGT due to longer fuel injection duration compared to 45 and 90 mm^3 FIQ.

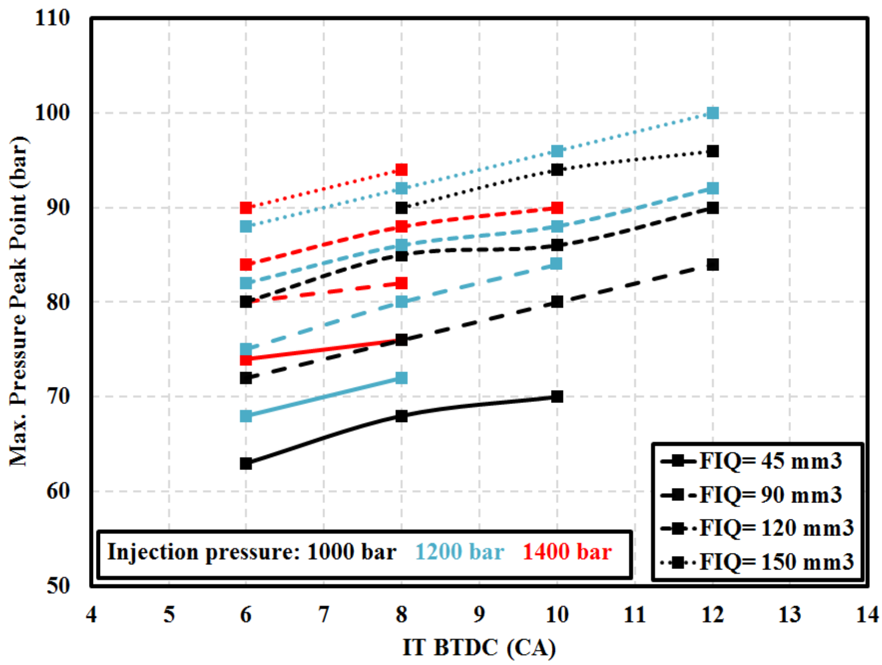

Figure 3. Effects of fuel injection characteristics on the in-cylinder Maximum Pressure Peak point

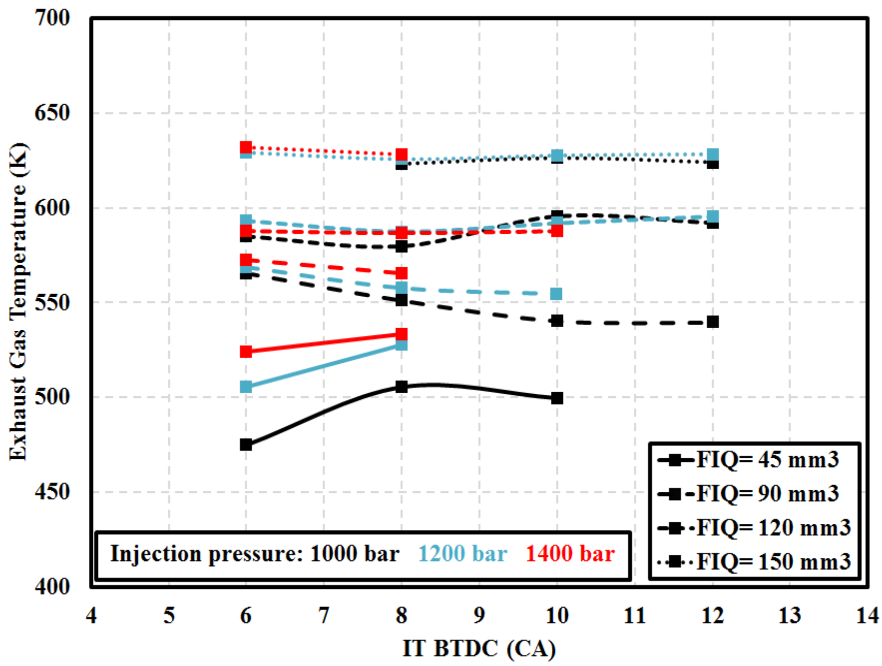

Figure 4. Effects of fuel injection characteristics on the exhaust gas temperature

Fig. (5) shows the simultaneous impacts of fuel injection timing, spraying pressure, and quantity on NOx emissions formation.

As shown in Fig. (5), NOx emissions increased by the addition of FIQ. As mentioned earlier, by increasing the amount of fuel quantity per cycle, more heat released during the compression stroke and led to higher combustion temperature. Thus, due to favorable conditions such as higher in-cylinder pressure and temperature, NOx emissions significantly increased. Moreover, advancing fuel injection timing resulted in more NOx formation in the exhaust gas. By advancing diesel injection timing, the large portion of air-fuel mixture burns in premixed combustion mode and led to higher pressure, temperature, and heat release rise rate. Thus, according to presented results in Fig. (5), NOx emissions significantly has increased. Furthermore, as indicated in Fig. (5), increasing fuel injection pressure has also led to an increment of NOx level due to the improvement of the air-fuel mixing process and faster combustion rate that resulted in a higher combustion temperature.

Fig. (6) reports the simultaneous impacts of fuel injection timing, spraying pressure, and quantity on soot emission formation.

As shown in Fig. (6), by increasing the fuel injection quantity per cycle, soot formation increased. Addition of FIQ that accompanied by lower AFR led to less oxygen concentration inside the combustion chamber and inefficient air-fuel oxidation process. Moreover, a higher amount of fuel leads to more carbon species involving in the combustion process that is one of the critical factors determining the amount of soot formation per cycle.

As illustrated in Fig. (6) for 45 mm^3 FIQ, fuel injection timing and spraying pressure have a negligible impact on soot formation, which can be due to the high AFR that leads to enhanced air-fuel mixture oxidation. It can be seen that for FIQ 90 mm^3, the number of soot particles has been decreased by advancing injection timing for 1000 bar spraying pressure due to higher combustion temperature and improved air-fuel oxidation process. However, for 1200 and 1400 bar spraying pressure, advancing fuel IT has slight effects on soot formation that can be due to shorter ID period which resulted in the less time available for the appropriate soot oxidation. In addition to that, for 120 mm^3 FIQ, fuel spraying pressure has slight impacts on the formation of soot particles, and by advancing diesel IT, soot level decreased by a small amount. Also, for 150 mm^3 FIQ, it can be seen that in Fig. (6), fuel injection timing and spraying pressure have adverse effects on soot formation which can be due to the fact that fuel injection into regions with lower pressure and temperature and also shorter ID period led to inefficient soot oxidation.

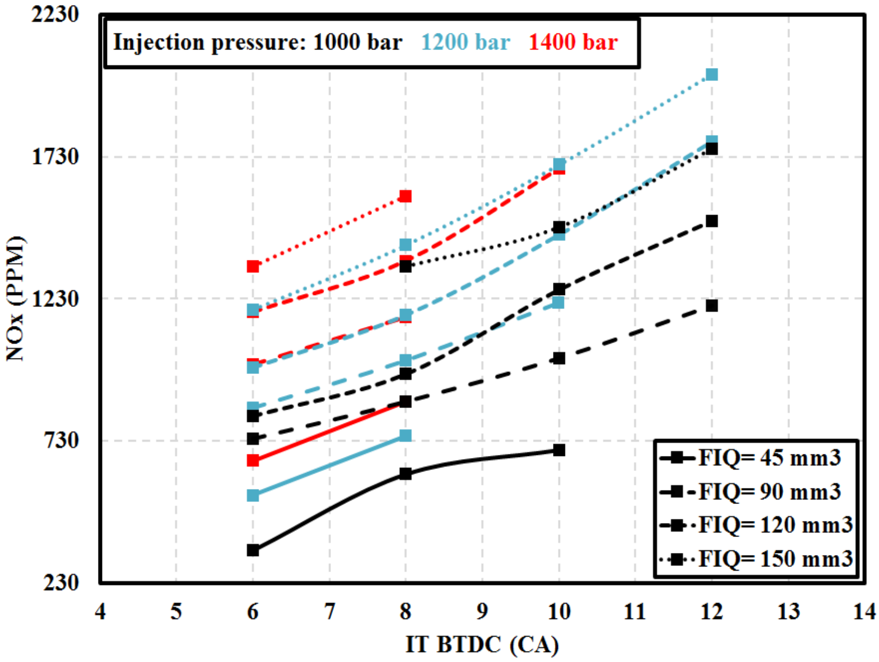

Figure 5. Effects of fuel injection characteristics on NOx emissions formation

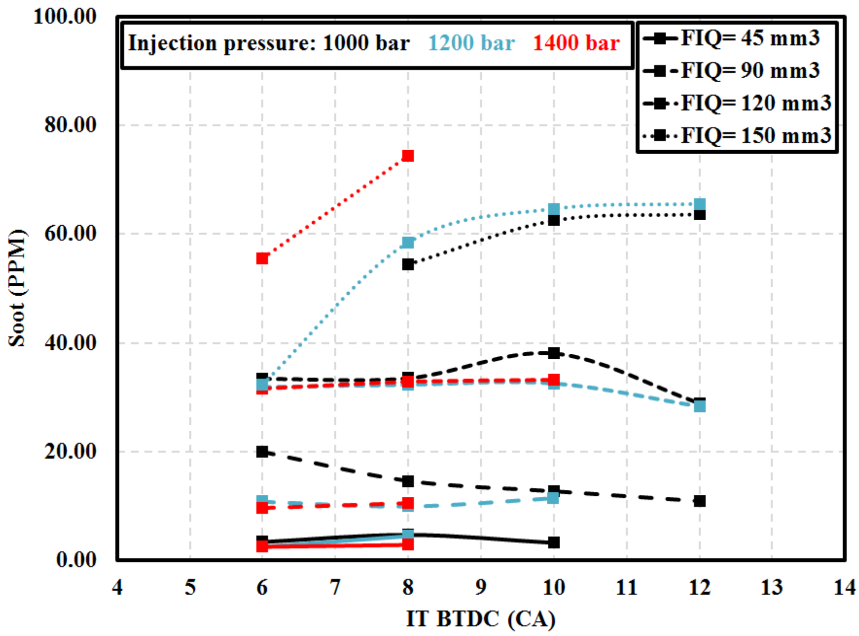

Figure 6. Effects of fuel injection characteristics on soot emission formation

According to the results presented in Fig. (5) and Fig. (6), it can be concluded that simultaneous addition of fuel quantity per cycle, spraying pressure, and advancing fuel IT, due to a reduction in overall AFR, higher combustion temperature, longer fuel injection duration, and shorter ID period led to the increment of both NOx and soot emissions.

Fig. (7) reports the simultaneous effects of fuel injection timing, spraying pressure, and quantity on brake power.

As shown in Fig. (7), by increasing fuel quantity per cycle, due to the increment of heat released by the combustion of the air-fuel mixture inside the cylinder, brake power has increased. It can be seen that for 45 mm^3 FIQ at 1000 bar spraying pressure, brake power initially increased then decreased. Advancing fuel IT led to the early start of combustion and more energy loss due to early combustion phase timing. However, for 8 CA BTDC injection timing, brake power improved due to higher combustion temperature and appropriate combustion phase timing compared to 6 and 10 CA BTDC ITs. Moreover, increasing fuel spraying pressure improved brake power due to enhanced air-fuel oxidation process and increased combustion temperature.

As illustrated in Fig. (7), For 90, 120, and 150 mm^3 FIQ, it can be seen that fuel injection timing and spraying pressure has no tangible effect on brake power. Thus, in this study, it can be concluded that fuel injection quantity has a significant impact on engine performance and determining the engine output power rather than two other fuel injection characteristics.

Fig. (8) indicates the simultaneous effects of fuel injection timing, spraying pressure, and quantity on BSFC.

As shown in Fig. (8), the addition of fuel quantity per cycle, led to a considerable reduction in BSFC due to higher combustion pressure and temperature caused by more heat released inside the engine cylinder. As can be seen in Fig. (8), for 45 mm^3 FIQ, fuel injection timing and spraying pressure have significant impacts on BSFC. By increasing fuel spraying pressure, results showed a significant improvement in BSFC due to higher in-cylinder MPPP and exhaust gas temperature caused by the enhanced air-fuel oxidation process. In addition to that, by advancing fuel injection timing, BSFC initially decreased for 1200 and 1400 bar spraying pressure but then increased for 1000 bar injection pressure at 10 CA BTDC IT.

Based on the results presented in Fig. (8), for 90 and 120 mm^3 FIQ, increasing fuel injection pressure due to an increment of MPPP and EGT, led to an improvement in BSFC. Furthermore, by advancing fuel IT, BSFC initially decreased then increased, which can be due to early combustion phase timing that caused by early ITs resulted in more energy loss during the compression stroke. However, for 150 mm^3 FIQ, injection timing and spraying pressure have a negligible impact on BSFC level that could be due to longer injection duration, which has slight effects on combustion phase timing.

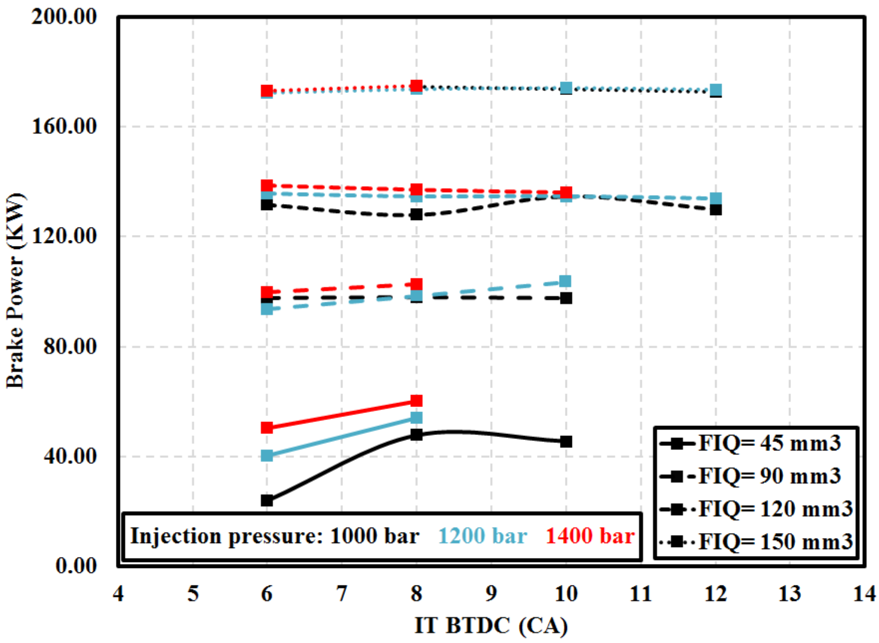

Figure 7. Effects of fuel injection characteristics on brake power

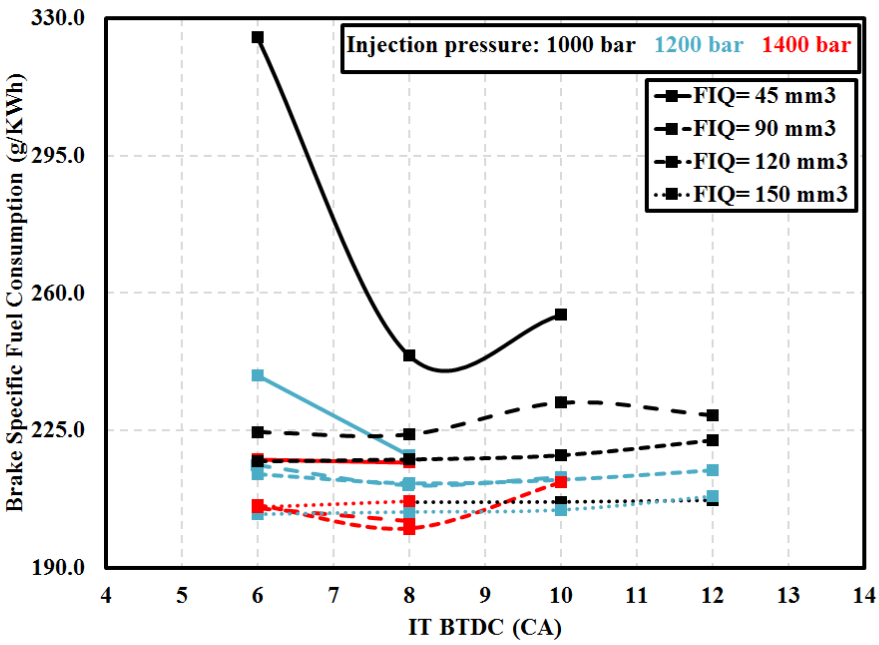

Figure 8. Effects of fuel injection characteristics on BSFC

According to indicated results in Fig. (7) and Fig. (8), it can be concluded that for lower FIQ (e.g., 45 mm^3), because of less fuel per cycle and shorter injection duration, fuel spraying pressure and injection timing have a significant impact on engine performance by determining the combustion phase timing and total energy loss per each cycle.

5. Conclusions

Simultaneous effects of diesel fuel injection characteristics such as injection timing, spraying pressure, and quantity on the combustion process, pollutant emissions formation, and performance in the D87 diesel engine were examined. In this study, the impacts of 36 various fuel injection strategies were investigated, and results showed that:

- Advancing fuel injection timing simultaneous with increasing spraying pressure and fuel quantity led to a large portion of air-fuel mixture burns in premixed combustion mode, shorter ID period and combustion duration, and also higher pressure rise rate that resulted in significant-high in-cylinder MPPP.

- By increasing the amount of fuel quantity per cycle (e.g., 150 mm^3), combustion temperature has significantly increased. However, due to longer injection duration, fuel spraying pressure and injection timing have a slight impact on the combustion phase, and EGT did not show tangible changes.
- Increasing fuel quantity per cycle and spraying pressure simultaneous with advancing fuel IT, due to higher combustion temperature, lower AFR, and shorter ID period led to the simultaneous increment of both NOx and soot emissions.
- For low FIQ (e.g., 45 mm^3) due to lower fuel quantity per cycle and shorter injection duration, injection timing and spraying pressure have a significant impact on engine performance by determining the time of the combustion phase and total energy loss per each cycle.

Abbreviations

CA	Crank Angle
CI	Compression-Ignition
DICI	Direct Injection Compression-Ignition
FIQ	Fuel Injection Quantity
ID	Ignition Delay
CO	Carbon Monoxide
CO_2	Carbon Dioxide
NOx	Nitrogen Oxides
PM	Particle Matter
UHC	Unburnt Hydro-Carbons
TDC	Top Dead Center
BTDC	Before Top Dead Center
BSFC	Brake Specific Fuel Consumption
RPM	Revolution Per Minute
EGR	Exhaust Gas Recirculation
MPPP	Maximum Pressure Peak Point
IT	Injection Timing
AFR	Air Fuel Ratio
EGT	Exhaust Gas Temperature

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