Fuel xxx (2013) xxx–xxx

Contents lists available at SciVerse ScienceDirect

Fuel

journal homepage: www.elsevier.com/locate/fuel

Effect of fuel injection timing and pressure on combustion, emissions and performance characteristics of a single cylinder diesel engine

Avinash Kumar Agarwal [a,*], Dhananjay Kumar Srivastava [a], Atul Dhar [a], Rakesh Kumar Maurya [a], Pravesh Chandra Shukla [b], Akhilendra Pratap Singh [a]

[a] *Engine Research Laboratory, Department of Mechanical Engineering, Indian Institute of Technology Kanpur, Kanpur 208 016, India*
[b] *Department of Civil Engineering, Indian Institute of Technology Kanpur, Kanpur 208 016, India*

HIGHLIGHTS

- Fuel injection pressure & timings affect engine performance, emissions and combustion.
- Rapid combustion, higher cylinder pressure & ROHR at advanced injection timings.
- Superior performance at lower FIP giving lower BSFC & emissions, & higher BTE.
- Emission characteristics improve with advanced fuel injection timings.
- Particulate number concentration in a CI engine increases with increasing engine load.

ARTICLE INFO

Article history:
Received 9 January 2012
Received in revised form 2 March 2013
Accepted 11 March 2013
Available online 28 March 2013

Keywords:
Diesel engine
Fuel injection pressures
Start of injection timings
Performance and emission characteristics
Combustion characteristics

ABSTRACT

For a diesel engine, fuel injection pressure (FIP) and injection timings are very important parameters, which influence the engine performance, emissions, and combustion. Other injection parameters affecting engine performance are rate of injection, injection pattern, number of injections etc. A single cylinder research engine was used to experimentally determine the effects of fuel injection strategies and injection timings on engine combustion, performance and emission characteristics. The experiments were conducted at constant speed (2500 rpm) with two FIPs (500 and 1000 bars respectively) and different start of injection (SOI) timings. Cylinder pressure and rate of heat release (ROHR) were found to be higher for lower FIPs however advanced injection timings gave higher ROHR in early combustion stages. Brake thermal efficiency (BTE) increased with increased injection pressures while exhaust gas temperature and brake mean effective pressure (BMEP) increased upto 500 bars. These parameters reduced slightly with increase in FIP. For advanced SOI, BMEP and BTE increased, while brake specific fuel consumption (BSFC) and exhaust gas temperature reduced significantly. Carbon dioxide (CO_2) and hydrocarbon (HC) emissions decreased however nitrogen oxide (NOx) emissions increased with increasing FIP. Lower CO_2 and HC emissions, and significantly higher NOx emissions were observed with advanced injection timings. Particulate number–size distribution increased with increasing engine load however it reduced with increasing FIP.

1. Introduction

Compression ignition (CI) engines, due to their excellent fuel efficiency and durability, have become popular power plants for automotive applications. This is globally the most accepted type of internal combustion engine used for powering agricultural implements, industrial applications, and construction equipment along with marine propulsion. However, emissions from diesel engines have been focused in increasingly stringent emission regimes because of their adverse health impact on humans. Diesel particulates are classified as ‘probable carcinogen’. Under tremendous pressure to comply with increasingly stringent emission norms adopted worldwide, mass emissions of particulate matter (PM) from diesel engines have been significantly reduced by automotive OEMs by employing improved exhaust gas after-treatment technologies [1]. In diesel engines, it is rather difficult to lower NOx and PM emissions simultaneously due to soot-NOx tradeoff. High NOx and PM emissions are still the main obstacle in the development of next generation conventional diesel engines.

Combustion, performance and emission characteristics of diesel engines depend on several factors like FIP, SOI, fuel quantity injected, number of injections (post- and pilot-), design of combustion chamber and nozzle spray patterns. High-pressure direct injection (HPDI) seems to be one of the most efficient ways to

---

* Corresponding author. Tel.: +91 512 259 7982; fax: +91 512 259 7408.
E-mail address: akag@iitk.ac.in (A.K. Agarwal).

0016-2361/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.fuel.2013.03.016

Please cite this article in press as: Agarwal AK et al. Effect of fuel injection timing and pressure on combustion, emissions and performance characteristics of a single cylinder diesel engine. Fuel (2013), http://dx.doi.org/10.1016/j.fuel.2013.03.016

comply with the stringent global emission norms. FIP for different generation of diesel engines varies from 200 to 2000 bars. Kato et al. [2] demonstrated using high fuel injection pressures as a means to reduce PM emissions without increasing NOx emissions. High FIPs seem to induce a very different spray structure than low FIP sprays used earlier [3]. This is mainly due to cavitation created in the nozzles at high FIPs, which results in significantly faster atomization [4]. Other studies [5,6] showed that higher FIPs improve fuel–air mixing, followed by faster combustion, which directly influences pollutant formation. Diesel spray characterization is usually done for parameters such as spray tip penetration, spray angle, droplet velocities, droplet sizes and distributions, and global spray structure. A good understanding of these characteristics is essential for increasing the combustion efficiency and reducing the environmental impact. High pressure difference across the injector nozzle is necessary to atomize the liquid fuel into small droplets in order to enable rapid vaporization as well for high jet penetration in the combustion chamber [7,8]. Droplets size distribution of a spray fundamentally affects CI engine combustion. Smaller fuel droplets vaporize rather quickly compared to larger droplets however their penetration is shorter therefore the size distribution needs to be optimized. Chen et al. reported that small droplets and high penetration depth of fuel jet enhances the fuel–air mixture quality, which provides shorter ignition delays and more complete combustion [8,9]. Lower FIPs gives larger droplet diameters, thus increasing ignition delay during combustion [9]. This also leads to higher cylinder pressures, which ultimately results in higher NOx emissions. When FIPs increase, spray droplet diameter distribution reduces. This leads to improved fuel–air mixture formation because of superior mixing during ignition delay, therefore smoke and CO emission reduce [10]. However, if FIP is too high, ignition delay period becomes too short. Hence, possibility of homogeneous mixing decreases and as a result, combustion efficiency reduces [11]. Bruneaux [12] investigated spray characteristics of common rail direct injection (CRDI) system in a high pressure, high temperature cell, which created conditions existing in a typical diesel engine. An increase of FIP was found to enhance the fuel atomization at the nozzle outlet, resulting in more distributed vapor phase, which improves mixing. Hence the fuel injection strategy is an important parameter in diesel engines to optimize the combustion, performance and tailpipe emissions.

These injection parameters also affect the particulate emission from diesel engines. High compression ratios, along with relatively high oxygen concentration in diesel combustion chamber delivers excellent thermal efficiency, and low CO and HC emissions in contrast with a comparable gasoline engine [13] however mass of particulates emitted from diesel engines is generally 10–100 times higher than SI engines [14–16]. Particulates are of concern from engine performance, durability and harmful environmental impact perspective. Higher particulate emissions result in reduced fuel economy because of fuel loss due to incomplete combustion. Interaction of these particulates results in increased wear of the engine components. Agarwal et al. [16] carried out experiments to investigate the characteristics of particulates and concluded that lubricating oil contaminated by diesel soot is a key factor responsible for higher engine wear [17].

Particulates have adverse environment impacts such as they affect human and live-stock health, lead to poor visibility, and soil the buildings. While attempting engine optimization, it is required to consider particulate numbers as well, along with particulate mass. Methods used for reducing the particulate mass such as increasing FIP, use of variable geometry turbochargers (VGT) and diesel particulate filters (DPF), tend to increase particulate numbers by reducing their size, which is likely to be more harmful for human health [18,19]. A serious study on the diesel particulate characterization is important because a significant proportion of diesel particulates have aerodynamic diameters less than 1 μm. Diesel particulates in this size range have a high probability of being inhaled and deposited in the respiratory tract, and potentially cause respiratory diseases and consequently damage the lungs [20,21].

Particles emitted from diesel engines can be completely characterized by gravimetric measurements, particle number-size distribution, particle surface area-size distribution, particle volume-size distribution, soluble organic fraction (SOF), elemental trace metals, elemental carbon (EC), organic carbon (OC), total carbon, and polycyclic aromatic hydrocarbons (PAHs) [22–26]. Agarwal et al. [16] reported an increase in particle number concentration at lower engine loads and particle number concentration reduction at higher engine loads with addition of 20% biodiesel to diesel.

In the present investigation, a flexible single cylinder research engine was used to experimentally evaluate the effect of fuel injection timings and FIP on combustion, emissions and performance. Mineral diesel was used as test fuel. This engine is capable of precisely controlling fuel injection parameters such as FIP, SOI and injected fuel quantity and the effect of variations in these parameters on engine combustion, performance and emission characteristics is evaluated. For particulate size and number distribution, engine exhaust particle sizer (EEPS) was used.

2. Experimental setup and procedure

2.1. Experimental setup

Schematic of the experimental setup is shown in Fig. 1. The experiments were conducted on a single cylinder research engine (AVL, 5402) equipped with fuel conditioning system, lubricating oil conditioning system and coolant condition system for experimental investigations in controlled conditions. For controlling the load and speed of the engine, AC dynamometer (Wittur Electric Drives, 2SB 3) was coupled with the research engine. The engine was equipped with common rail direct injection system, with advanced features for controlling the FIP and SOI timing. FIP could be varied up to 1400 bars and this system was capable of multiple injections (2 pilot injections and 2 post injections in addition to the main injection). State-of-the-art intake air measurement system (ABB Automation Products, Sensyflow P) and gravimetric fuel flow-meter (AVL, 733S.18) were used. Cylinder pressure was measured using a piezoelectric pressure transducer (AVL), which was connected to a charge amplifier (AVL) and finally to a high speed combustion data acquisition and analysis system (AVL, Indismart) for exhaustive combustion investigations. Test engine specifications are given in Table 1.

An exhaust gas emission analyzer (AVL, 444) was used to measure CO, CO_2, HC, NOx in the exhaust. For particulate size-number distribution, EEPS spectrometer (TSI, EEPS3090) was deployed. This instrument can measure particle sizes ranging from 5.6 nm to 560 nm with a maximum measurable number concentration of 10^8 particles/cm^3 of engine exhaust. It has sizing resolution of 16 channels per decade comprising of total 32 channels. Number concentration of particulates in the engine out exhaust is higher than the maximum measuring range of EEPS therefore diesel exhaust is diluted 560 times using a rotating disk thermo-diluter (Matter engineering, md19-2e), before entering the EEPS.

2.2. Experimental procedure

Effects of fuel injection parameters on combustion, performance, emissions and particulate size-number distribution were investigated by varying fuel injection timings and FIPs at different engine loads. During the experiment, lubricating oil and coolant temperatures were maintained at 80 °C and 60 °C respectively

Please cite this article in press as: Agarwal AK et al. Effect of fuel injection timing and pressure on combustion, emissions and performance characteristics of a single cylinder diesel engine. Fuel (2013), http://dx.doi.org/10.1016/j.fuel.2013.03.016

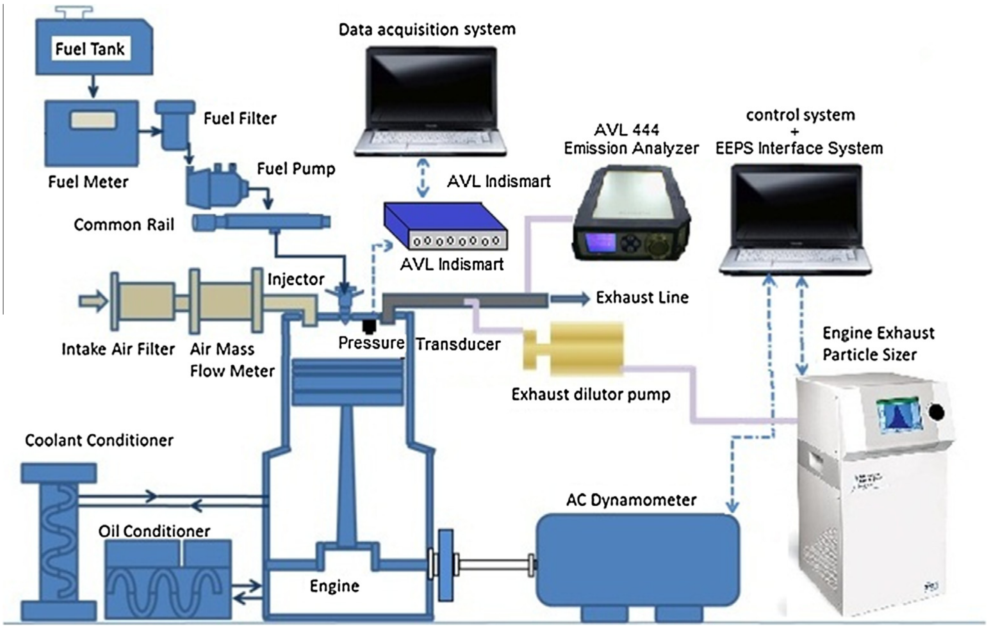

Fig. 1. Schematic of the experimental setup.

Table 1
Technical specifications of the test engine.

Engine parameter	Specification
Engine model	AVL 5402
Number of cylinders	1
Cylinder bore/stroke	85/90 mm
Swept volume	510.7 cc
Compression ratio	17.5
Inlet ports	Tangential & swirl inlet port
Maximum power	7 kW
Rated speed	4200 rpm
Fuel injection pressure	200–1400 bars
Fuel injection system	Direct injection
High pressure system	Common rail CP4.1 BOSCH
Engine management system	AVL-RPEMS + ETK7 BOSCH
Valves per cylinder	4 (2 inlet, 2 exhaust)
Valve train type	DOHC cam follower
Liner type/base	Wet

using lubricating oil conditioning system and coolant conditioning system. Temperature of fuel at the inlet of high pressure fuel pump was maintained at 20 °C using fuel conditioning system. Engine torque was increased by increasing the fuel injection pulse duration. FIP and SOI timing were controlled using INCA based engine management system (EMS), which has flexibility for user defined control of various fuel injection parameters. SOI timing and injection duration were also measured by acquiring signals for the injector opening current during fuel injection process. Experiments were performed at two FIPs, 500 and 1000 bars at constant engine speed of 2500 rpm. At 500 bars FIP, SOI timing was varied from 15° BTDC to 9.375° BTDC. At 1000 bars FIP, SOI timing was varied from 9.375° BTDC to 4.875° BTDC because further advancement of SOI timings was increasing the rate of pressure rise beyond safe limits. The SOI timings were determined after complete engine sweep over the entire range of parameters.

For engine performance analysis, brake specific fuel consumption (BSFC) and brake thermal efficiency (BTE) were calculated from measured fuel consumption rate, torque and speed data. Brake specific mass emissions were calculated from measured raw exhaust emission concentrations. For combustion analysis, variation of cylinder pressure with crank angle position was recorded for 200 consecutive combustion cycles using high speed data acquisition system. For elimination of cycle-to-cycle combustion variability, average of these 200 combustion cycles was analyzed to calculate rate of heat release (ROHR) and mass burn fraction (MBF) durations.

For measurement of particulate size-number distribution, exhaust gas was diluted by sheath air by using thermo-dilutor. Concentration of particulates in engine exhaust was calculated by accounting for the dilution factor. Particulate size-number distribution data was recorded for 1 min at 1 Hz frequency and average of these 60 particulate size-number distribution sweeps was analyzed and presented in various graphs in the following section.

3. Results and discussion

The results of the experiment are given separately in the subsections on combustion analysis, performance analysis, emission analysis and particulate analysis.

3.1. Combustion analysis

Cylinder pressure data analysis is the most effective tool to analyze engine combustion behavior because cylinder pressure history directly influences power output, combustion characteristics and engine-out emissions. In this study, cylinder pressure data was acquired w.r.t. crank angle using a high speed data acquisition system. Using this data, P–θ diagrams can be drawn, which provide information about the 'start of combustion (SOC)', 'rate of pressure rise (ROPR)', ROHR as well as maximum cylinder pressure (P_{max}).

Fig. 2 shows the variation of cylinder pressure and ROHR w.r.t. crank angle at different engine loads and SOI timings. Maximum cylinder pressure increases with increasing fuel quantity injected. It happens due to richer mixture formed inside the chamber, which burns more rapidly in early stages of combustion (premixed combustion) and remaining fuel burns in later stages (diffusion combustion) and requires longer duration. ROHR curve also follows similar pattern and richer mixture conditions burns with longer combustion duration. Advancing SOI leads to longer ignition delay, which promotes premixed combustion and higher maximum

Please cite this article in press as: Agarwal AK et al. Effect of fuel injection timing and pressure on combustion, emissions and performance characteristics of a single cylinder diesel engine. Fuel (2013), http://dx.doi.org/10.1016/j.fuel.2013.03.016

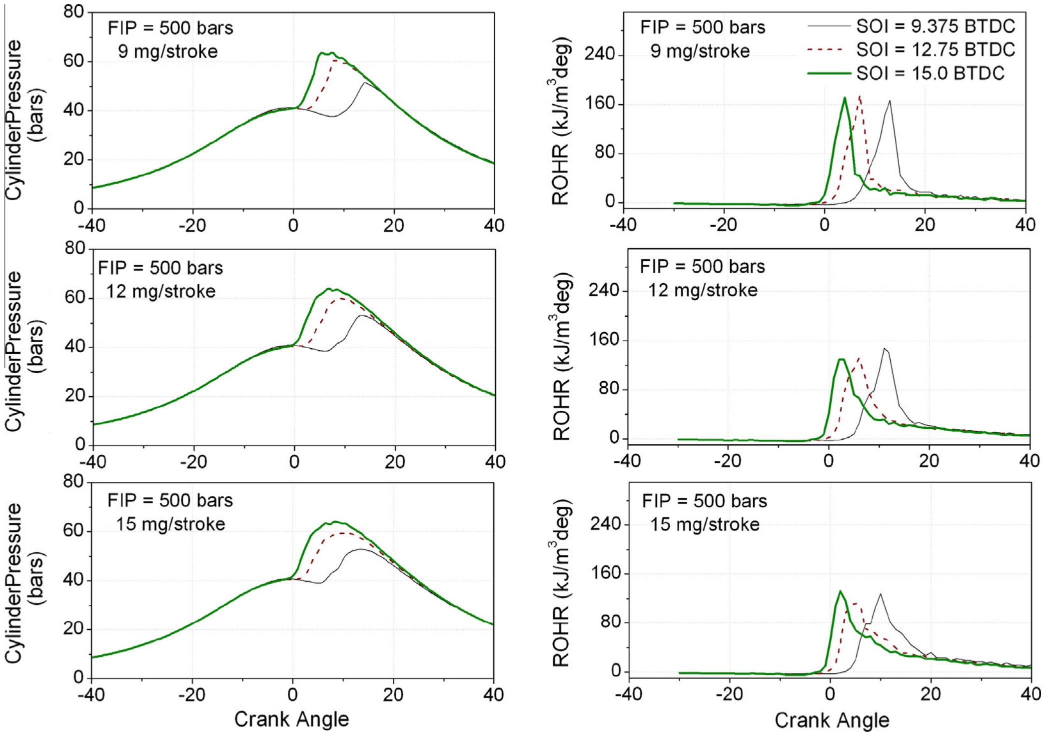

Fig. 2. Cylinder pressure and ROHR variations for different injected fuel quantities and SOI timings at constant FIP of 500 bars.

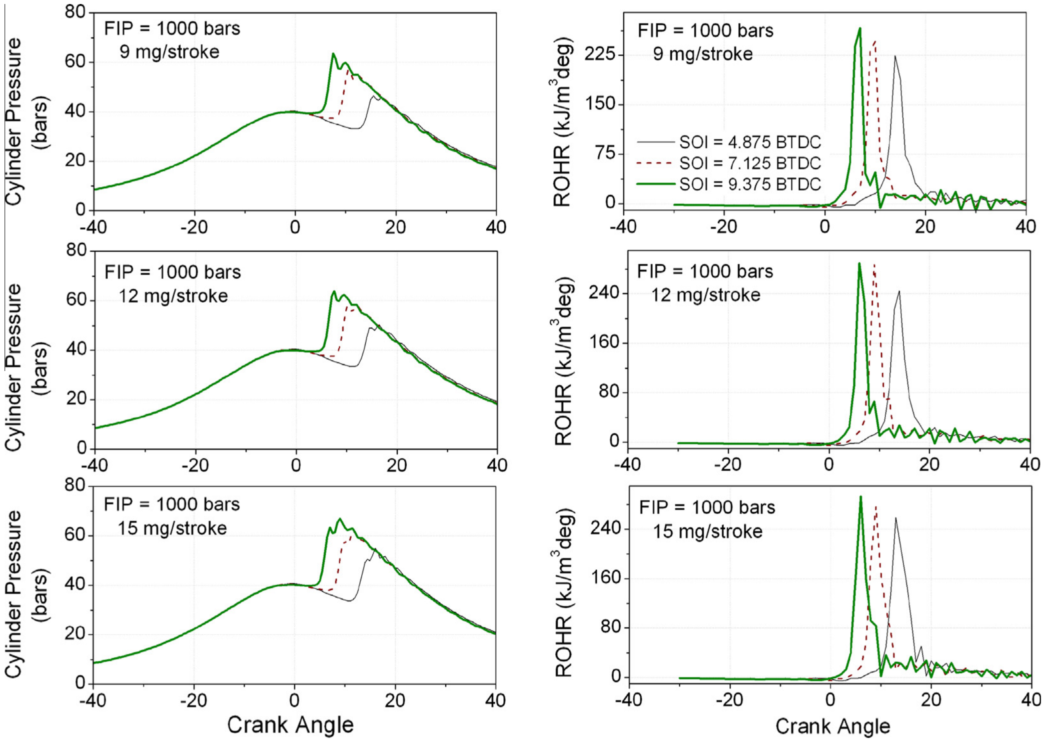

Fig. 3. Cylinder pressure and ROHR variations for different injected fuel quantities and SOI timings at constant FIP of 1000 bars.

cylinder pressure and higher ROHR peak can be seen. When SOI was retarded and it came closer to top dead center (TDC) in compression stroke, ignition delay became shorter, which led to higher fuel fraction burning in diffusion combustion thereby lowering maximum cylinder pressure. Due to this shorter ignition delay, pressure peak was smaller and it also shifted away from TDC position in expansion stroke as compared to earlier SOI conditions. This shift was clearly visible in ROHR curves where the peak of the curve shifted away from TDC in expansion stroke with retarded injection.

Fig. 3 shows the cylinder pressure and ROHR curves for varying injection conditions at 1000 bars FIP. It was similar to Fig. 2 however one can notice knocking conditions especially at higher engine

Please cite this article in press as: Agarwal AK et al. Effect of fuel injection timing and pressure on combustion, emissions and performance characteristics of a single cylinder diesel engine. Fuel (2013), http://dx.doi.org/10.1016/j.fuel.2013.03.016

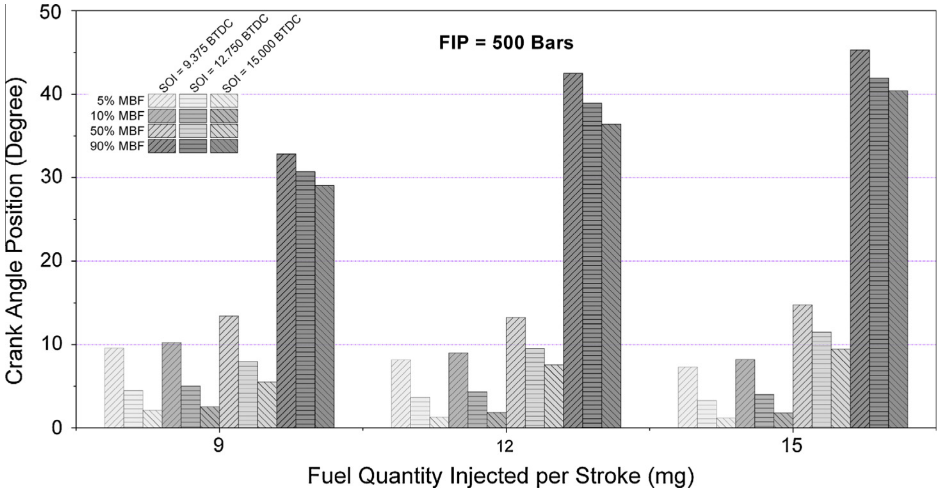

Fig. 4. MBF variations with varying fuel injection quantities and SOI at FIP of 500 bars.

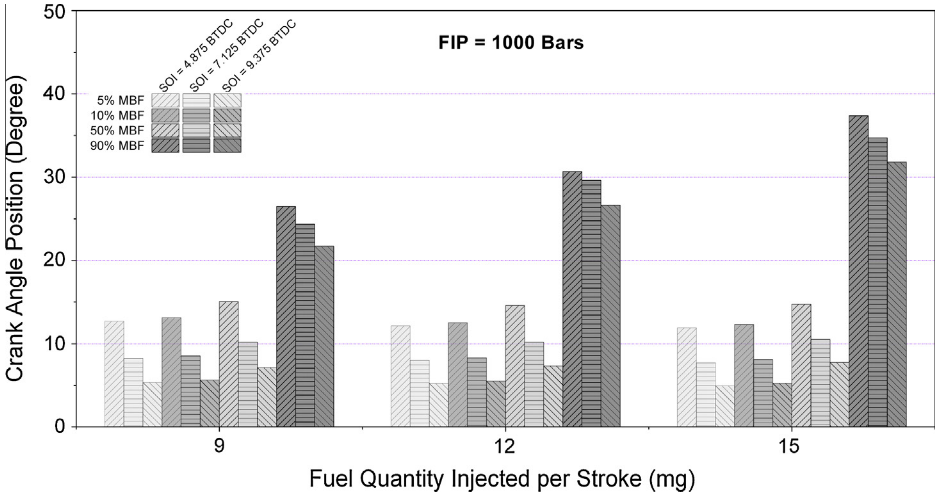

Fig. 5. MBF variations with varying fuel injection quantities and SOI at FIP of 1000 bars.

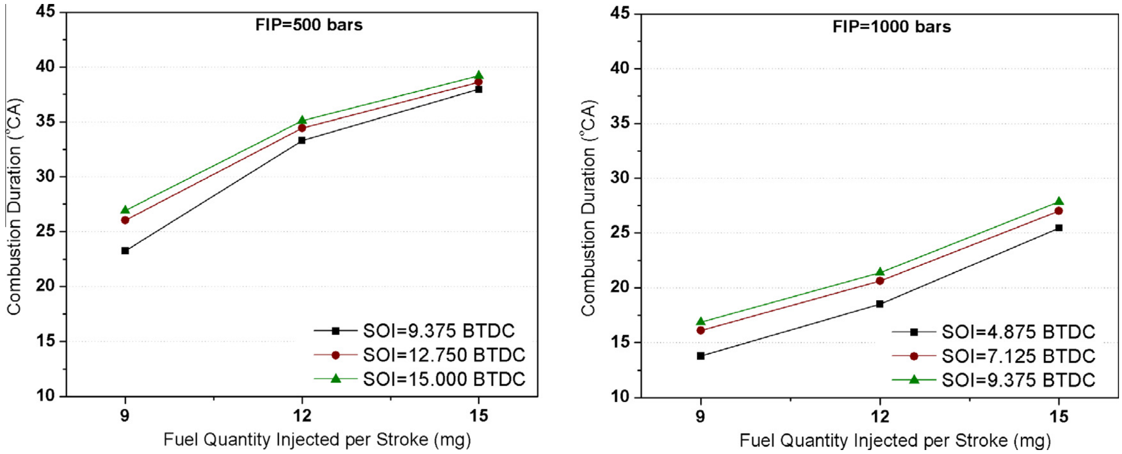

Fig. 6. Combustion duration for varying fuel injection quantities at different SOI at two FIPs.

loads. This knocking tendency increased with advanced injections due to availability of more fuel quantity in early stages of combustion, which promoted erratic combustion due to extremely high ROHR. Higher FIP (1000 bars) gave extremely high ROHR. This was due to finer fuel atomization at higher FIPs, which promoted mixing and increases ROHR [7,10].

Please cite this article in press as: Agarwal AK et al. Effect of fuel injection timing and pressure on combustion, emissions and performance characteristics of a single cylinder diesel engine. Fuel (2013), http://dx.doi.org/10.1016/j.fuel.2013.03.016

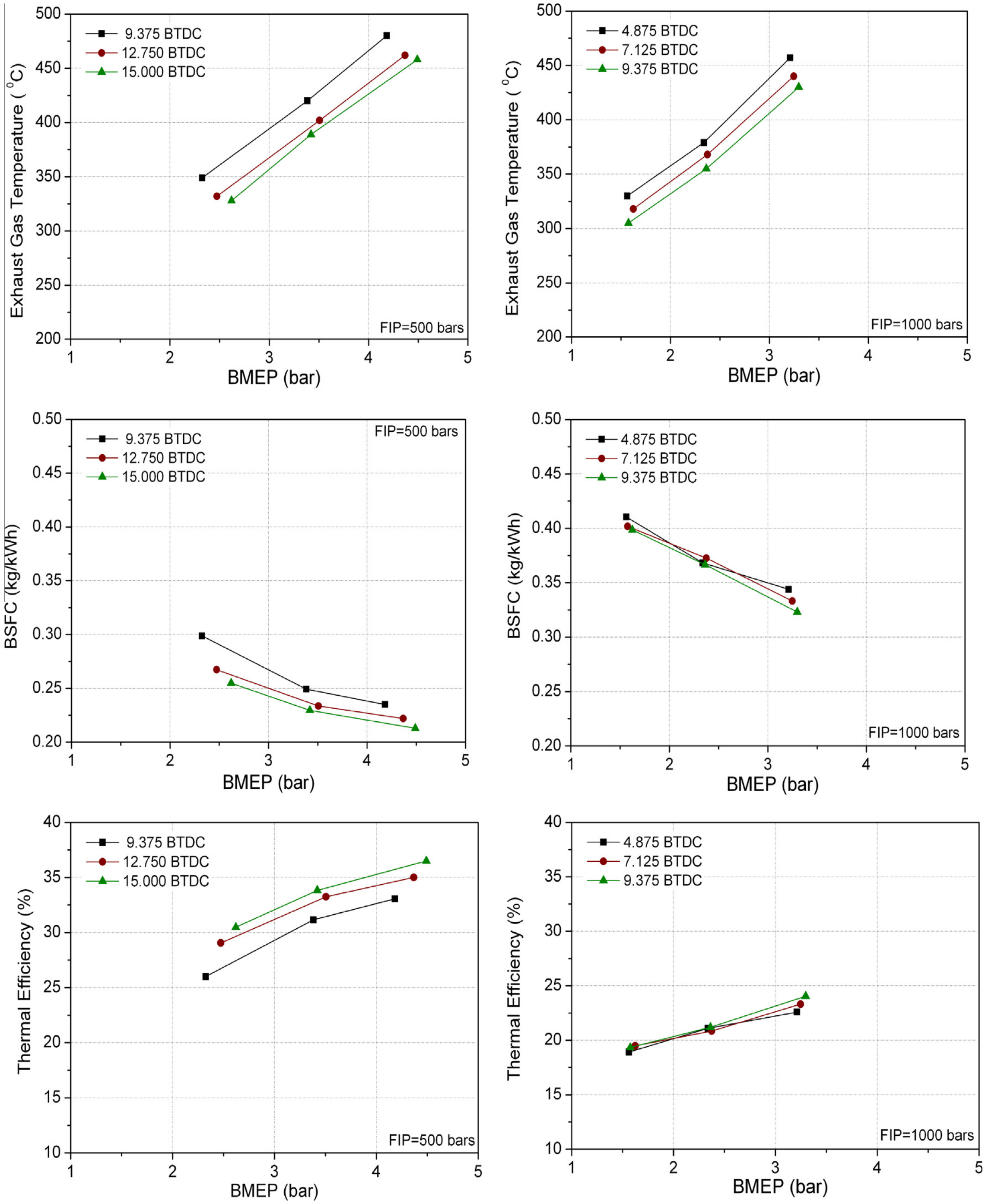

Fig. 7. Engine performance parameter for varying FIP and SOI.

Fig. 4 shows that combustion duration increased with greater fuel quantity injected. It happens mainly due to longer diffusion combustion. There was very small variation in crank angle position at MBF_{50} because in almost every condition, premixed combustion happened at the same rate and the fuel burned very quickly in premixed combustion. However SOI timings significantly affected premixed mass burn fraction. For advanced injection timing (15° BTDC), injection delay was high, which increased ROHR in premixed combustion phase (Fig. 2) hence combustion duration was shorter. This tendency decreased with retarding SOI conditions.

Similar experiments were performed at 1000 bars FIP (Fig. 5). In this case also, almost similar results were obtained however combustion duration decreased significantly due to significantly higher ROHR compared to 500 bars FIP (Fig. 4). It can be noticed that crank angle position at MBF_{10} was quite close to TDC for 1000 bars FIP, which indicated relatively lower ignition delay for higher FIPs [9,27]. This conclusion can be drawn by comparing the data for SOI 9.375 BTDC only, because this was the only common SOI condition at both FIPs.

Crank angle position for MBF_{50} was quite similar for both FIPs however total combustion duration (MBF_{90}–MBF_{10}) for 500 bars FIP was significantly higher compared to 1000 bars FIP due to combustion of a large part of injected fuel in diffusion combustion phase, as seen in Fig. 6.

Please cite this article in press as: Agarwal AK et al. Effect of fuel injection timing and pressure on combustion, emissions and performance characteristics of a single cylinder diesel engine. Fuel (2013), http://dx.doi.org/10.1016/j.fuel.2013.03.016

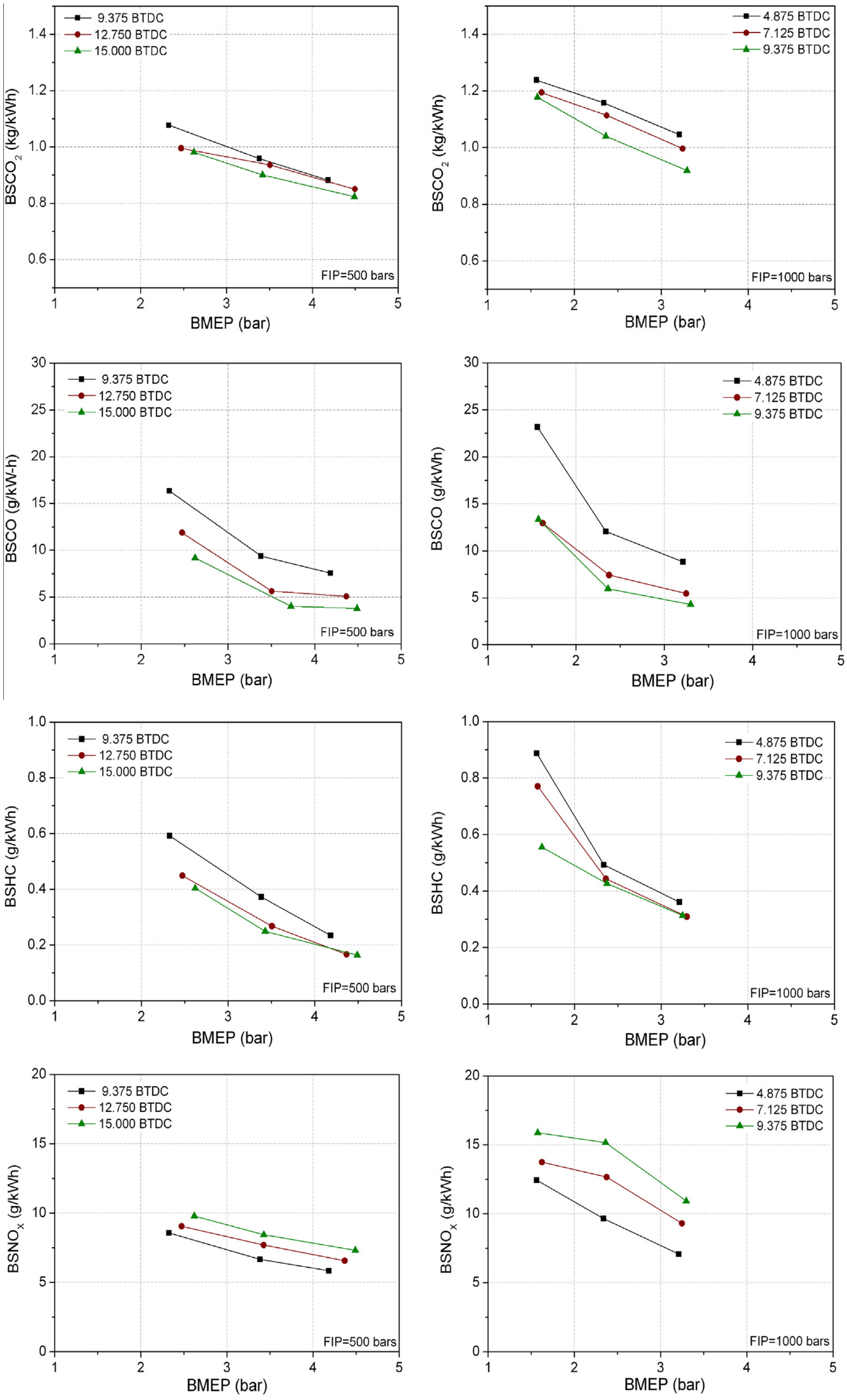

Fig. 8. Mass emissions of regulated emission with engine load for varying SOI at two FIPs.

3.2. Performance analysis

Experiments were performed to analyze exhaust gas temperature (EGT), BSFC and BTE at two different FIPs (500 and 1000 bar) and three different SOI timings.

Fig. 7 shows that the EGT always increased (in all six experimental conditions) with increasing engine load (BMEP) because of the increased fuel quantity injected. However higher exhaust gas temperatures were seen for lower FIP (500 bar) compared to higher FIP (1000 bar). It happened due to larger droplet size

Please cite this article in press as: Agarwal AK et al. Effect of fuel injection timing and pressure on combustion, emissions and performance characteristics of a single cylinder diesel engine. Fuel (2013), http://dx.doi.org/10.1016/j.fuel.2013.03.016

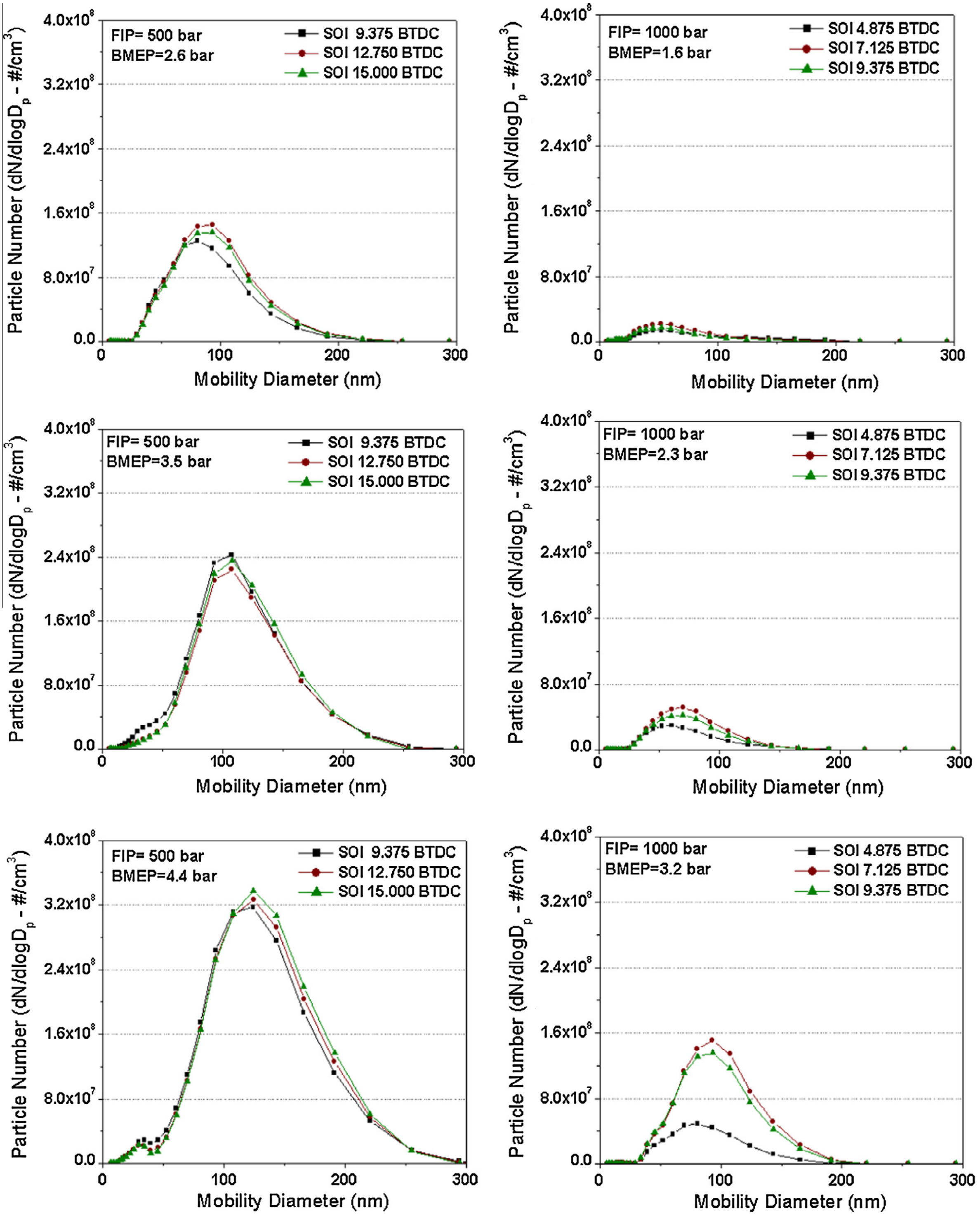

Fig. 9. Particulate size-number distribution for varying fuel injection pressures and start of injection timings.

distribution inside the combustion chamber, which promoted heterogeneous combustion, while finer droplet size distribution at higher FIP gave relatively better fuel–air mixing and smoother combustion [7–10,27,28]. EGT was found to be lower for advanced SOI conditions due to main heat release occurring closer to TDC in the expansion stroke, which provided enough time for hot gases to expand and cool down before the exhaust valves were opened. This caused superior heat utilization and more cooling of combustion products hence reduced exhaust gas temperature. Similarly, BSFC decreased in all experimental conditions with increasing engine load. This reduction in BSFC can be explained by the fact that as the engine load increases, there was continuous improvement in combustion quality and efficiency. Cylinder pressure increased with increasing engine load and increasing injected fuel quantity, which burned more efficiently therefore fuel consumption per unit brake power produced i.e. BSFC decreased. For advanced injection timings, a large amount of evaporated fuel accumulates in the combustion chamber during the ignition delay period, and burns quickly, which leads to rapid heat release rate and causes sudden increase in temperature and pressure in the cylinder. As most of

Please cite this article in press as: Agarwal AK et al. Effect of fuel injection timing and pressure on combustion, emissions and performance characteristics of a single cylinder diesel engine. Fuel (2013), http://dx.doi.org/10.1016/j.fuel.2013.03.016

the fuel burns in premixed combustion phase, it causes very high peak heat release rate and hence power output increases. At very high FIP (1000 bars), BSFC was higher than lower FIP (500 bar) due to relatively inferior combustion characteristics, which led to lower power output at 1000 bars FIP. BTE followed exactly reverse trend as that of BSFC and increased with increasing engine load in all experimental conditions. BTE was seen to be significantly lower at very high fuel injection pressures. It happened due to smaller droplet size distribution and larger jet penetration of the fuel spray, which enhanced mixing and reduced ignition delay period [7–10,27–29] but got into knocking regime. Shorter ignition delay led to knocking and fluctuations in cylinder pressure and temperature (Figs. 2 and 3) and shorter combustion duration (Figs. 4 and 5). This result also showsed that BTE increased with advanced SOI due to similar reasons as BSFC.

3.3. Emission analysis

Fig. 8 describes the mass emission characteristics of different exhaust gases (CO_2, CO, HC and NOx) for different engine loads at varying experimental conditions. The results showed that $BSCO_2$ emissions decreased with increasing engine load however advanced SOI further reduced $BSCO_2$ emission, which indicated towards more efficient combustion with advanced fuel injection timings, which is an observation similar to the one made in Fig. 7. $BSCO_2$ emissions increased significantly at higher injection pressures due to poor combustion characteristics including knocking, which led to lower thermal efficiency (Fig. 7) as well as higher $BSCO_2$ emissions.

BSCO and BSHC emissions both follow the same trend. BSCO and BSHC emissions also decreased with increasing engine load. It happened due to higher cylinder gas temperatures at higher engine loads, which led to more efficient combustion of fuel at higher temperature, producing lower quantities of these emissions. At similar BMEP, CO and HC mass emissions decreased with increasing FIP due to superior fuel–air mixing in the combustion chamber [9,10,27,28]. Advanced SOI improved air–fuel mixing due to availability of more time for mixing process; therefore this led to lower CO and HC mass emissions as well.

Formation of NOx is highly dependent on the maximum temperature of the burning gases, oxygen content, and residence time available for the reactions to take place at these extreme conditions [10,30,31]. Fig. 8 shows that mass emission of NOx decreased with increasing engine load due to relatively higher increase in power output as compared to raw NOx emissions. BSNOx emissions increased significantly with increasing FIP due to higher ROHR during premixed combustion phase (Figs. 2 and 3). Similarly advanced SOI also increased BSNOx emissions due to higher ignition delay and more time available for NOx chemistry to take place, which ultimately increased the BSNOx emissions. It is interesting to note that BSNOx emissions were higher for 1000 bars FIP compared to 500 bars FIP. This was because at 500 bars FIP, longer time available for NOx chemistry to take place dominated and at 1000 bars FIP, higher ROHR dominated the NOx chemistry.

3.4. Particulate analysis

Particulate size-number distribution was measured at different SOI timings at two FIPs (500 and 1000 bars). To investigate the effect of injection timings on particulates, SOI was varied from 15° BTDC to 9.375° BTDC for 500 bars FIP and from 9.375° BTDC to 4.875° BTDC for 1000 bars FIP, just like earlier tests. Particulate size-number distribution was measured after thermal stabilization of the test engine at every engine operating condition.

Fig. 9 shows the variation of particulate size-number distribution at different SOIs at two FIPs. Particulate size-number distribution increased with increasing load at all FIPs and SOI timings. This was because, air–fuel ratio decreased with increasing engine load in CI engines due to injection of higher fuel quantities in every engine cycle, which created fuel-rich zones inside the combustion chamber. Due to lack of available oxygen in these fuel-rich zones, particulate formation increased. Similar trend was also reported by Virtanen et al. [32]. Shifting of peak of the particulate size-number distribution towards higher particulate diameters with increasing engine load confirmed that these conditions were also more favorable for agglomeration and formation of larger particles. At lower engine loads and lower FIPs, particulate number concentrations were lowest for retarded injection timings and number concentration increased with advancing injection timing. At higher injection pressures, total particulate number concentration in the exhaust decreased due to relatively superior fuel–air mixing [9,10,27,28]. At higher engine loads, advancing the injection timing reduced the total particulate concentration. Minimum particulate concentration was observed at 1000 bar FIP at 4.875° BTDC SOI. At lower FIPs, cylinder pressure and temperature became very critical for fuel atomization and fuel–air mixing. If fuel was injected at higher cylinder pressures (i.e. retarded injection timings), large number of smaller fuel droplets formed due to better atomization. Process of air–fuel mixing also depends on time available for droplets to mix with surrounding air after the atomization and before the start of combustion. The time available for mixing of fuel droplets with air increased with advanced fuel injection however fuel droplet size also increased due to lower cylinder temperatures and pressures prevailing at the time of advanced fuel injection. These two factors affected the particulate formation in opposite direction. At 1000 bars FIP, particulate number concentration first increased with retarded SOI timing and then decreased due to combined effect of these two factors.

4. Conclusions

The experiments were performed at constant speed (2500 rpm) with two FIPs (500, and 1000 bars) and different SOI timings. Pressure variations and ROHR showed superior combustion characteristics at lower FIP (500 bars), while at higher FIP (1000 bars), knocking was observed under certain engine operating conditions. Advanced injection timings led to rapid combustion hence higher ROHR was observed in early stages of combustion. MBF results also supported these findings. Engine performance was superior at low FIPs leading to lower BSFC and higher BTE at all engine loads. These parameters can be further improved by advancing the SOI. Lower mass emission of CO_2 CO, HC and NOx was observed at lower FIP. Emission characteristics improved by advancing the SOI. Particulate number concentration in a CI engine increased with increasing engine load. Increasing the FIP reduced the number concentration of particulates of all sizes at all loads. At higher FIP, advancing the injection timings reduced the particulate number concentration because advanced SOI timings provided longer time for fuel–air mixing before the start of combustion. At lower FIP, particulate number concentration first increased and then decreased with retarding SOI timings because mixing at lower FIP was more sensitive to cylinder pressure and temperature along with time available for mixing before the SOC.

References

[1] Kirchstetter TW, Harley RA, Kreisberg NM, Stolzenburgh MR, Hering SV. On-road measurement of fine particulate and nitrogen oxide emissions from light- and heavy-duty motor vehicles. Atmos Environ 1999;33:2955–68.

[2] Kato T, Tsujimara K, Shintani M, Minami T, Yamaguchi L. Spray characteristics and combustion improvement of a DI diesel engine with high pressure fuel injection. SAE 1989:890265.

[3] Baritaud TA, Heinze TA, Coz JF. Spray and self-ignition visualization in a DI diesel engine. SAE 1994:940681. Tamaki et al..

Please cite this article in press as: Agarwal AK et al. Effect of fuel injection timing and pressure on combustion, emissions and performance characteristics of a single cylinder diesel engine. Fuel (2013), http://dx.doi.org/10.1016/j.fuel.2013.03.016

[4] Bruneaux G, Verhoeven D, Baritaud T. High pressure diesel spray and combustion visualization in a transparent model diesel engine. SAE 1999. 1999-01-3648.
[5] Dec J. A conceptual model of DI diesel engine. SAE 1997:970873.
[6] Agarwal AK, Chaudhary V, Agarwal A, Shukla PC. Comparative study of macroscopic spray parameters and fuel atomization behaviour of SVO (jatropha), its biodiesel and blends. Therm Sci 2013;17(1):217–32.
[7] Birch S. Fuel injection: the inside story. Tech Briefs SAE 2000.
[8] Chen PC, Wang WC, Roberts WL, Fang T. Spray and atomization of diesel fuel and its alternatives from a single-hole injector using a common rail fuel injection system. Fuel 2013;103:850–61.
[9] Wang X, Huang Z, Kuti OA, Zhang W, Nishid K. Experimental and analytical study on biodiesel and diesel spray characteristics under ultra-high injection pressure. Int J Heat Fluid Flow 2010;31:659–66.
[10] Zhang G, Qiao X, Miao X, Hong J, Zheng J. Effects of highly dispersed spray nozzle on fuel injection characteristics and emissions of heavy-duty diesel engine. Fuel 2012;102:666–73.
[11] Celikten I. An experimental investigation of the effect of the injection pressure on engine performance and exhaust emission in indirect injection diesel engines. Appl Therm Eng 2003;23:2051–60.
[12] Bruneaux G. Liquid and vapour spray structure in high-pressure common rail diesel injection. Atomization Spray 2001;11:533–56.
[13] McClellan RO. Am Ind Hygiene Assoc J 1986;47(I):1–13.
[14] Kittelson DB. Engines and nanoparticles: a review. J Aer Sci 1998;29(5/6):575–88.
[15] Gupta T, Kothari A, Srivastava DK, Agarwal AK. Measurement of number and size distribution of particles emitted from a mid-sized transportation multipoint port fuel injection gasoline engine. Fuel 2010;89:2230–3.
[16] Agarwal AK, Gupta T, Kothari A. Particulate emissions from biodiesel vs diesel fuelled compression ignition engine. Renew Sustain Energ Rev 2011;15:3278–300.
[17] George S, Balla S, Gautam M. Effect of diesel soot contaminated oil on engine wear. Wear 2007;262:1113–22.
[18] Donaldson K, Li XY, MacNee W. Ultrafine (nanometre) particle mediated. J Aer Sci 1998;29(5/6):553–60.
[19] Kim H, Sung Y, Jung K, Choi B, Lim MT. Size distributions and number concentrations of particles from the DOC and CDPF. J Mech Sci Technol 2008;22:1793–9.
[20] Dockery DW, Pope CA, Xu X, Spengler JD, Ware JH, Fay ME, et al. An association between air pollution and mortality in six US cities. Massachusetts medical society. J Med 1993;329:1753–9.
[21] Pope CA, Thun MJ, Namboodriri MM, Dockery DW, Evans JS, Speizer FE, et al. Particulate air pollution as a predictor of mortality in a prospective study of US adults. Am J Resp Crit Care Med 1995;151:669–74.
[22] Burtscher H. Physical characterization of particulate emissions from diesel engines: a review. Aer Sci 2005;36:896–932.
[23] Neeft JPA, Makkee M, Moulijn JA. Diesel particulate emission control. Fuel Process Technol 1996;47:1–69.
[24] Maricq MM. Chemical characterization of particulate emissions from diesel engines: a review. Aer Sci 2007;38:1079–118.
[25] Dwivedi Dipankar, Agarwal Avinash K, Sharma Mukesh. Particulate emission characterization of a biodiesel vs. diesel-fuelled compression ignition transport engine: a comparative study. Atmos Environ 2006;40:5586–95.
[26] Kittelson D, Johnson J, Watts W, Wei Q, Drayton M, Paulsen D, et al. Diesel Aer Sampling Atm. SAE 2000. 2000-01-2212.
[27] Kuti OA, Zhu J, Nishida K, Wang X, Huang Z. Characterization of spray and combustion processes of biodiesel fuel injected by diesel engine common rail system. Fuel 2013;104:838–46.
[28] Jinghua Z, Hong Wei H, Xuejun L, Fangxi X, Li J. Study about effects of EGR and injection parameters on the combustion and emissions of high-pressure common-rail diesel engine. In: 2nd International Conference on Industrial Mechatronics and Automation; 2010.
[29] Youn IM, Park SH, Roh HG, Lee CS. Investigation on the fuel spray and emission reduction characteristics for dimethyl ether (DME) fueled multi-cylinder diesel engine with common-rail injection system. Fuel Process Technol 2011;92:1280–7.
[30] Heywood JB. Internal Combustion Engine Fundamentals. New York: McGraw-Hill; 1988.
[31] Sayin C, Canakci M. Effects of injection timing on the engine performance and exhaust emissions of a dual-fuel diesel engine. Energ Convers Manage 2009;50:203–13.
[32] Virtanen AKK, Ristimaki JM, Vaaraslahti KM, Keskinen J. Effect of engine load on diesel soot particles. Environ Sci Technol 2004;38:2551–6.

Please cite this article in press as: Agarwal AK et al. Effect of fuel injection timing and pressure on combustion, emissions and performance characteristics of a single cylinder diesel engine. Fuel (2013), http://dx.doi.org/10.1016/j.fuel.2013.03.016