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Comparative experimental evaluation of performance, combustion and emissions of laser ignition with conventional spark plug in a compressed natural gas fuelled single cylinder engine

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HIGHLIGHTS

- Comparative evaluation of laser ignition (LI) and spark ignition (SI).
- Air–fuel ratio and ignition timings were varied.
- Brake power was marginally higher for LI compared to SI.
- Combustion advanced in LI by 1–4° CA compared to SI.
- COV_{IMEP} in LI was lower compared to SI.

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ABSTRACT

Laser is emerging as a strong concept for alternative ignition in spark ignition engine. Laser ignition has potential advantages over conventional spark plug ignition. Laser ignition system is free from spark electrodes hence there is no loss of spark energy to the electrodes, which are also free from erosion effect. In addition, there is flexibility in choosing spark location and it offers excellent performance under high in-cylinder pressures. In this paper, performances of laser ignition and conventional spark ignition systems are comparatively evaluated in terms of in-cylinder pressure variation, combustion stability, fuel consumption, power output and exhaust emissions at similar operating conditions of the engine.

1. Introduction

Stringent norms for engine exhaust emissions and demand for higher thermal efficiency have compelled the automotive manufacturers and researchers to develop new engine technologies and alternative fuels. Compressed natural gas (CNG) is one of the most promising alternative fuel because of its widespread availability, economic viability and environmental benefits. CNG fuelled engine can be operated with higher compression ratio because of its high octane number compared to gasoline, which results in superior thermal efficiency and reduced fuel consumption. Engine exhaust emissions are lower compared to other hydrocarbon fuels due to its high hydrogen-to-carbon ratio. Engine exhaust emissions can be reduced by in-cylinder combustion optimization and exhaust gas after-treatment. Therefore, it is of great interest to introduce engine technologies, which can address the need for both improved thermal efficiency and reduced engine exhaust emissions. Lean mixture combustion is a promising concept to increase engine efficiency and reduced exhaust emissions from spark ignition engines [1–3]. However, lean mixture combustion is associated with two major challenges namely loss of power output and slower flame speeds. These challenges restrict the lean limit of air–fuel mixtures. Full potential of lean mixture combustion can be extracted by overcoming these two challenges.

Loss of engine power output can be compensated by boosting the charge density in the combustion chamber. Increased charge density however requires higher secondary coil voltage to initiate combustion in a spark ignition engine, which is using conventional spark ignition system. The voltage required to produce the spark depends on factors such as pressure inside the combustion chamber at the time of ignition, distance between the electrodes, and cylinder gas temperature. Providing the required voltage under these conditions would lead to spark electrode erosion. Since lean

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mixtures have relatively slower flame speed than stoichiometric mixtures, any technique which may provide a stronger and reliable initial flame kernel or increase the air–fuel mixture burning rate, would be beneficial. Flame speed in the lean burn SI engine can be increased either by generating turbulence in the cylinder [4] or by shortening the flame travel distance for the same mixture strength. Reduction in flame travel path can be realized by employing multiple spark plugs in each cylinder or by placing the ignition point at an optimum location inside the combustion chamber [5,6]. It is rather challenging to install multiple spark plugs in multi-cylinder engines because of already overcrowded cylinder head. Optimum spark location inside the combustion chamber is also difficult in case of conventional spark ignition systems because spark location is always very close to the top of combustion chamber. Therefore, a durable, high-energy, electrode-less ignition system with controlled energy deposition in the plasma, with flexibility to change the ignition location is a desirable option for overcoming these limitations faced in lean-burn SI engines. Laser ignition system meets most of these requirements and, offers several advantages for igniting lean mixtures.

The concept of laser ignition is based on focusing the pulsed laser beam tightly to create a very small spot size in such a manner that the energy density at the focal point is enough to generate a localize plasma (Fig. 1). Laser pulse energy is further absorbed by the plasma to raise the local temperature and pressure. If the energy threshold is high enough, ignition takes place in the surrounding air–fuel mixture.

There are different mechanisms by which laser interacts with gaseous medium to initiate combustion such as (i) thermal ignition [7–10], (ii) photochemical ignition [11–13], (iii) resonant ignition [14] and, (iv) non-resonant ignition [15–18]. For engine applications, non-resonant mechanism is generally used because in this mechanism, where laser wavelength is independent of the absorption wavelength of gaseous molecules. Laser ignition was done in this study using non-resonant mechanism. Laser ignition offers several advantages over conventional spark plug ignition system for engine applications. Minimum ignition energy required for combustion decreases with increasing cylinder pressure using laser ignition [15]. This trend is exactly opposite of what is observed in conventional spark ignition system, where spark energy required for combustion increases with increasing cylinder pressures [19]. Location of ignition point in the combustion chamber can be optimized in laser ignition by changing the focal length of the converging lens. Flame kernel can be moved away from the combustion chamber walls thus the heat transfer losses through the cylinder walls can be reduced thereby enhancing the overall efficiency. It is expected that ignition delay and combustion duration will be shorter in laser ignition compared to conventional spark plug ignition. Thus NOx emission will be lower in laser ignition. There are no heat losses at spark electrodes in case of laser ignition because this is an electrode-less ignition concept. Thus approximately entire laser pulse energy can be transferred to the combustible mixture using an optimized laser and optics. This helps in initial flame kernel development which influences the combustion and cycle-to-cycle variations.

Several researchers have investigated combustion using laser ignition in a constant volume combustion chamber, which simulated typical engine operating conditions towards the end of compression stroke [15–18,20–24]. Several parameters like minimum ignition energy, flame kernel evolution, ignition delay, rate of pressure rise, effects of laser and optics, etc. were measured for different fuels in these studies. These experiments were helpful in developing laser ignition system for engine. Srivastava et al. [24] carried out laser ignition of CNG–air mixture in a constant volume combustion chamber and investigated evolution of flame kernel for varying lambda. In the early stages of flame development, a toroidal shape of the kernel was observed. Toroidal shape of flame kernel was similar to conventional spark plug ignition system. After some time, a front lobe formed, which propagated towards the incoming laser beam. This was a peculiar feature of laser-induced ignition. The shape of the flame kernel was structurally identical for all air–fuel ratios. It was observed that the front lobe of the flame kernel disappeared after some time for relative air–fuel ratios (λ) of 1.6 and 1.7. Dale et al. [25] first demonstrated laser ignition of an internal combustion engine in 1978. They compared the engine performance using laser ignition vis-a-vis conventional spark plug system. Higher rate of pressure rise was reported for laser ignition. Lean limit of air–fuel ratio was extended from 22.5:1 to 27.8:1 for the laser ignition. Over the years, laser ignition of engine did not gather momentum due to good performance offered by conventional spark plug systems and poor efficiency and high cost of lasers available. However, stringent emission legislations and increased emphasis on lean-burn combustion are compelling the engine developers and scientists around the world to consider laser as an ignition source for the internal combustion engines. Biruduganti et al. [26] compared the laser and conventional spark ignition systems on a natural gas engine at fixed λ by varying the spark timing. They reported that fuel conversion efficiency and COV of IMEP were comparable for both ignition systems. Laser ignition performed much better compared to spark ignition due to higher peak pressures and faster combustion. NOx emission was higher for laser ignition compared to spark ignition at identical operating condition of the engine. Bihari et al. [27] conducted laser ignition of single cylinder research engine fuelled with CNG. Lean misfire limit extended from an equivalence ratio of 0.55–0.50 with laser ignition at 900 rpm engine speed. Combustion stability was

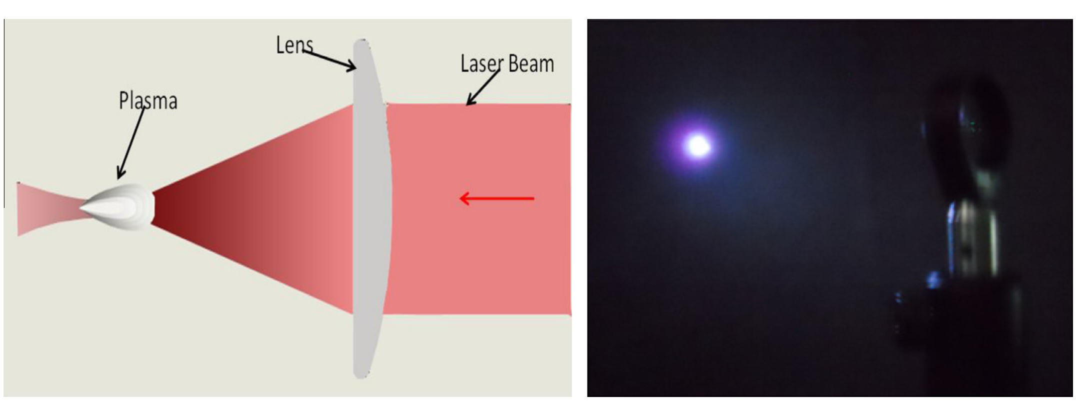

Fig. 1. Plasma formation in air (direction of incoming laser is from right to left).

also superior with laser ignition. In addition, approximately 50% NOx reduction was also observed in case of laser ignition. Herdin et al. [28] emphasized upon the importance of quality of beam profile which has a direct bearing on the minimum ignition energy required for combustion. McMillian et al. [29] extended the total operating envelope of the engine, which was defined as the area between knock and misfire limits, by 46% compared to conventional spark ignition system. NOx emissions reduced by approximately 50% for laser ignition but hydrocarbon emissions were comparable for both ignition systems. Mullett et al. [30] investigated the effect of laser parameters such as laser pulse energy, beam quality, minimum beam waist diameter, and focal length on engine combustion, performance and stability. In this paper, a comparative performance evaluation of laser ignition and conventional spark ignition is done in terms of in-cylinder pressure variations, combustion stability, fuel consumption, power output and exhaust emissions at similar operating condition of the engine, using CNG in an engine, which is typically used in decentralized power generation sector.

2. Experimental setup

Laser ignition was performed in a customized naturally aspirated, water cooled, four-stroke single cylinder engine. Bore and stroke of the engine were 102 mm and 116 mm respectively and compression ratio was 9.8. Engine was coupled with an eddy current dynamometer. Dynamometer was also connected to a 3φ A/C motor via a gear box, which could be engaged to start the engine and automatically gets disengaged, once the engine starts. Air–fuel ratio was determined by separately measuring air and fuel flow rates. A laminar flow element (LFE) (Meriam, 50MC2-2F) was installed for the intake air flow rate measurement. CNG was stored in a cylinder at a very high pressure, therefore a pressure reducer was used to bring down the pressure to 1 bar for the experiments. Reduced pressure fuel line was connected immediately upstream of throttle in the air intake system. CNG mass flow rate was measured by Coriolis force based fuel flow meter (Emerson, CMF010M). Two types of ignition system employed in the experiment were conventional spark ignition system and laser ignition system. Engine was first operated with conventional spark ignition system. A variable spark timing system (Altronic, CD200) was installed and the experiments were performed for different spark timings. A magnetic pickup sensor was installed on the camshaft for triggering the ignition system controller. After performing the experiments with conventional spark ignition system, laser was used as an ignition source. A Q-switched Nd: YAG laser operating at 1064 nm wavelength with pulse duration of 6–9 ns was used to ignite the combustible mixture. A laser spark plug was installed in the cylinder head in place of a conventional spark plug. Laser spark plug consists of two parts: a window holder and a lens holder. Details of laser spark plug can be seen in Ref. [6] from our group. Lens cannot withstand harsh condition prevailing in the combustion chamber, therefore a sapphire window (thickness 3 mm; diameter 12.5 mm) was used for protection and sealing the combustion gases from attacking/damaging the lens. A 30 mm focal length converging lens was used to focus the laser inside the combustion chamber. Laser plasma was kept at the same location as that of conventional spark plug plasma for the sake of comparative investigations under identical conditions. Laser beam propagated in atmosphere from laser head to the laser spark plug. A customized electronic circuit triggered the laser at a specific crank angle. Schematic of the laser ignition of engine experiment is shown in Fig. 2.

Cylinder pressure variations were measured by a piezoelectric pressure transducer (Kistler, 6013C) installed in the engine cylinder head. Signals from the pressure transducer were amplified and converted to voltage signals by a charge amplifier (Kistler, 5015). These signals were acquired by a high speed combustion data acquisition system (Hi-Techniques, meDAQ). Engine exhaust emissions were measured using raw exhaust gas emission analyzer (Horiba, EXSA-1500).

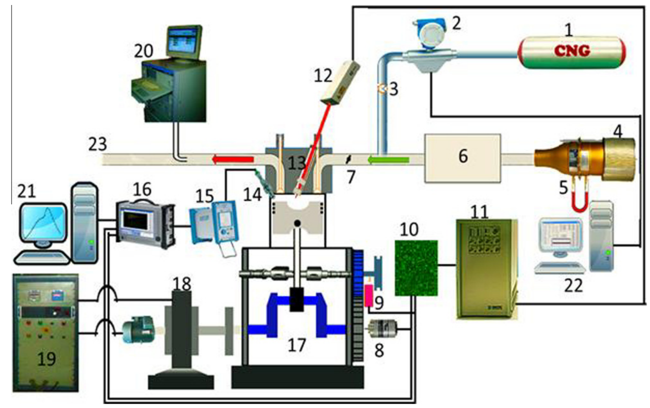

Fig. 2. Experimental setup for laser ignition: 1. CNG cylinder. 2. CNG mass flow meter. 3. CNG flow control valve. 4. Laminar flow element. 5. U tube manometer. 6. Air box. 7. Throttle. 8. Shaft encoder. 9. TDC sensor. 10. Laser trigger Circuit. 11. Laser power supply. 12. Nd: YAG laser. 13. Laser spark plug. 14. Piezo-electric pressure transducer. 15. Charge amplifier. 16. High speed combustion data acquisition system. 17. Single cylinder engine. 18. Eddy current dynamometer. 19. Dynamometer controller. 20. Raw exhaust gas emission analyzer. 21. DAQ computer. 22. Computer for ignition control and CNG flow meter. 23. Exhaust manifold.

All engine experiments were carried out at constant engine speed (1500 rpm) at wide open throttle condition. A conventional electric spark plug was installed and experiments were carried out at different λ and ignition timings. Ignition timing was varied from 17° BTDC to 37° BTDC and λ was varied from 1.35 to 0.90 in these investigations. Maximum brake torque (MBT) timing was determined for different λ. Based on the MBT, conventional spark ignition and laser ignition systems were compared at three ignition timings i.e., 21° BTDC, 25° BTDC and 29° BTDC. For laser ignition, converging lens with 30 mm focal length was used to focus the laser beam inside the engine combustion chamber. Engine combustion, performance and exhaust emissions were measured for each ignition timing and λ and were compared for both ignition systems.

3. Results and discussion

Experiments were done to show the variation in cylinder pressure and rate of heat release (ROHR) w.r.t. crank angle for spark ignition and laser ignition at different λ. Pressure-crank angle data set used for comparative combustion analysis is an average data set of 100 consecutive engine cycles. In the engine experiments of laser ignition, a converging lens of 30 mm focal length was used to focus the laser beam. This was the shortest focal length which could be used in the experiments because of mechanical and design constraints of this particular engine. Plasma position was maintained at approximately same position inside the engine combustion chamber for both laser ignition as well as spark ignition. λ was varied from 1.35 to 0.9. Ignition timing was fixed at 25° BTDC for both spark ignition and laser ignition.

It is evident from Fig. 3 that maximum cylinder pressure and maximum ROHR increased with decreasing λ for both spark ignition and laser ignition. When mixture was made richer ($\lambda < 1$), maximum cylinder pressure and maximum ROHR decreased. Crank angle position for maximum pressure and maximum ROHR also shifted towards TDC with decreasing λ.

In spark ignition combustion, maximum pressure increased from 34.5 bars at 16.5° ATDC for λ = 1.35 to 44.3 bar at 16.5° ATDC

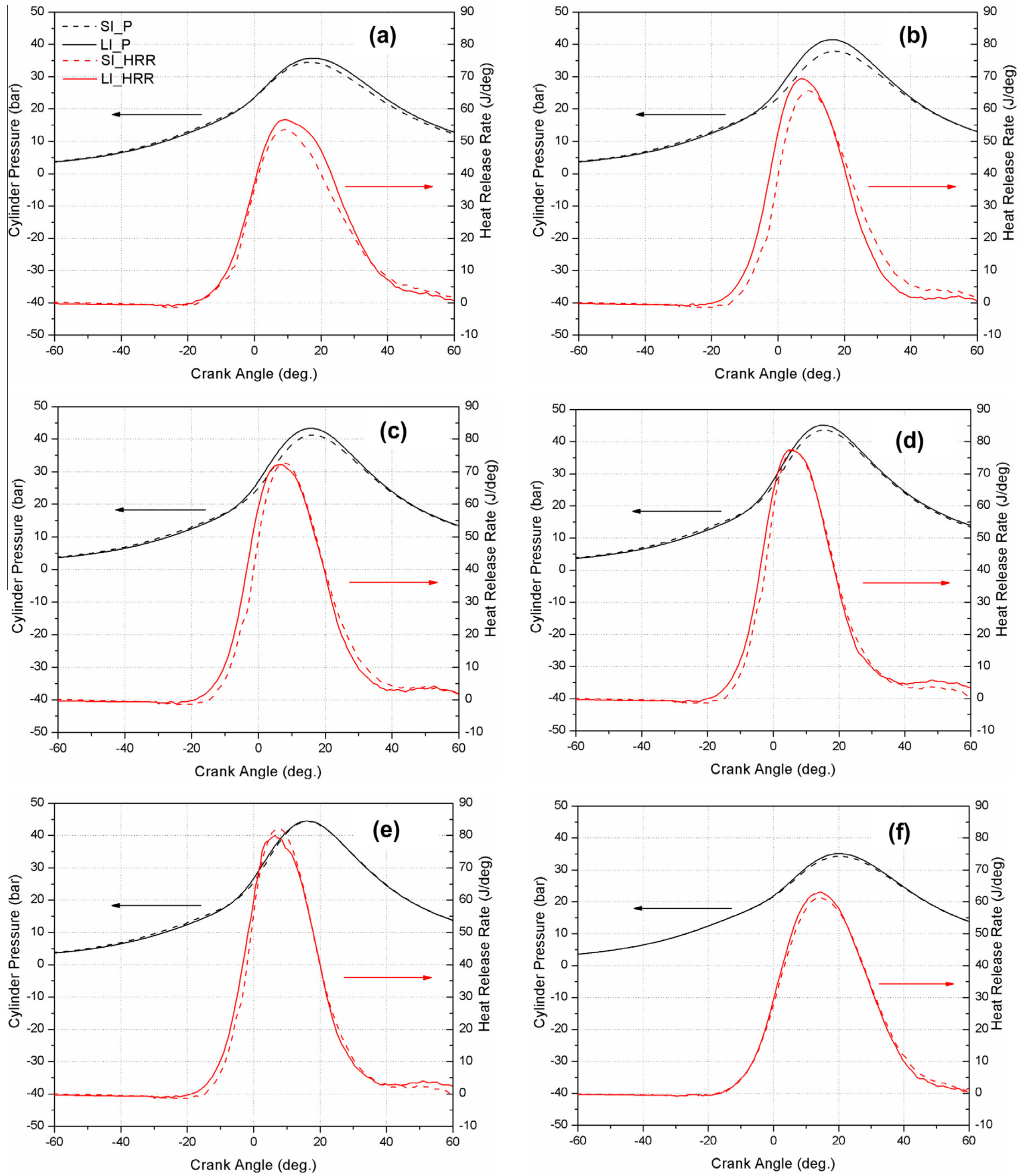

Fig. 3. Comparative variation of cylinder pressure and ROHR for SI and LI with crank angle position for (a) $\lambda = 1.35$, (b) $\lambda = 1.2$, (c) $\lambda = 1.15$, (d) $\lambda = 1.10$, (e) $\lambda = 1.00$, and (f) $\lambda = 0.90$ at ignition timing of 25° BTDC.

for stoichiometric mixture. Maximum ROHR increased from 53.6 J/deg at 9.5° ATDC for $\lambda = 1.35$ to 82 J/deg at 8° ATDC for stoichiometric mixture. Whereas in laser ignition combustion, maximum pressure increased from 35.7 bar at 17.5° ATDC for $\lambda = 1.35$ to 44.5 bar at 16° ATDC for stoichiometric mixture. Maximum ROHR increased from 56.6 J/deg at 9° ATDC for $\lambda = 1.35$ to 80 J/deg at 6.5° ATDC for stoichiometric mixture.

This trend of maximum pressure and crank angle position for maximum pressure is directly related to the flame speed and the efficiency of combustion. Flame speed increases as the mixture becomes richer. Highest flame speed was observed for slightly richer mixture than stoichiometric ($\lambda \sim 0.9$) however it decreased with further enrichment of the mixture. At higher λ (leaner mixtures), combustion was constrained by lower fuel availability and at lower λ (richer mixture), combustion was constrained by lower air availability. In Fig. 3a for $\lambda = 1.35$, flame speed would be expectedly lower therefore combustion took place mostly in the later part of the expansion stroke. As λ decreased from 1.35 to 1 (Fig. 3a–e), flame speed increased and crank angle position for the maximum pressure shifted towards TDC for both, spark ignition as well as laser ignition.

It can be noted from Fig. 3 that maximum cylinder pressure was marginally higher for laser ignition compared to spark ignition. Differences in the maximum cylinder pressures between spark ignition and laser ignition decreased as λ decreased. For $\lambda = 1.2$, the maximum cylinder pressure was 41.5 bar in case of laser ignition whereas in spark ignition, it was only 37.9 bar. The crank angle position of maximum cylinder pressure was 16° ATDC in laser ignition and in spark ignition, it was 17.5° ATDC. Thus, a higher maximum cylinder pressure and earlier peak pressure position was observed for laser ignition compared to spark ignition under identical operating conditions of the engine. However, cylinder pressure variation was almost similar for stoichiometric ($\lambda = 1$) and richer ($\lambda = 0.9$) mixtures. ROHR was higher in laser ignition compared to spark ignition. Thus the laser ignition led to superior and faster combustion compared to spark ignition and resulted in relatively higher maximum cylinder pressure and higher ROHR for lean mixtures. Similar tests were also conducted for different combustion timings i.e. 21° BTDC and 29° BTDC for the sake of comparison. Combustion characteristics of laser ignition were same as discussed above compared to spark ignition at these operating conditions also. Maximum cylinder pressure and ROHR increased for advanced ignition timings. It was also observed that phasing of maximum pressure and maximum ROHR relative to TDC decreased with advanced ignition timings.

Higher maximum pressure and higher ROHR were observed for laser ignition compared to spark ignition, probably because combustion started earlier in case of laser ignition. Mass burn fraction (MBF) is generally used to characterize different stages of combustion. Different combustion stages were calculated from the MBF curves. Fig. 4 shows different stages of combustion for laser ignition and spark ignition w.r.t. λ at varying ignition timings of 21° BTDC (Fig. 4a), 25° BTDC (Fig. 4b) and 29° BTDC (Fig. 4c). In each of these figures, 5% MBF, 50% MBF and 90% MBF are represented as MBF-5, MBF-50 and MBF-90 respectively. Start of combustion is defined as the time when a very small fraction of air–fuel mixture is burned. Researchers have used either 1%, or 5% or 10% MBF to define the start of combustion [31]. MBF-5 is considered as "start of combustion" in this investigation. End of combustion is defined as the time, when bulk of air–fuel mixture is already burnt. MBF-90 is considered as "end of combustion" in the present investigations.

It can be seen from Fig. 4 that combustion starts earlier in laser ignition compared to spark ignition for all λ and ignition timings. Combustion started earlier in laser ignition by approximately 1–4° CA compared to spark ignition. Ignition delay, which is defined as the crank angle interval between the spark discharge and beginning of combustion, would also be lower for laser ignition compared to spark ignition because of earlier start of combustion for identical ignition timings. MBF-50 and end of combustion (MBF-90) is observed to be earlier also for laser ignition compared to spark ignition however after certain value of λ, it becomes almost similar. MBF-5, MBF-50 and MBF-90 were found to decrease with decreasing λ.

Earlier start of combustion can be explained on the basis of energy absorption mechanisms by laser and spark plasma. There is a fundamental difference in the way, in which, laser generated plasma absorbs energy compared to electrical spark generated plasma. The optical frequency of laser beam is higher than the plasma frequency, therefore laser beam is capable of propagating well into

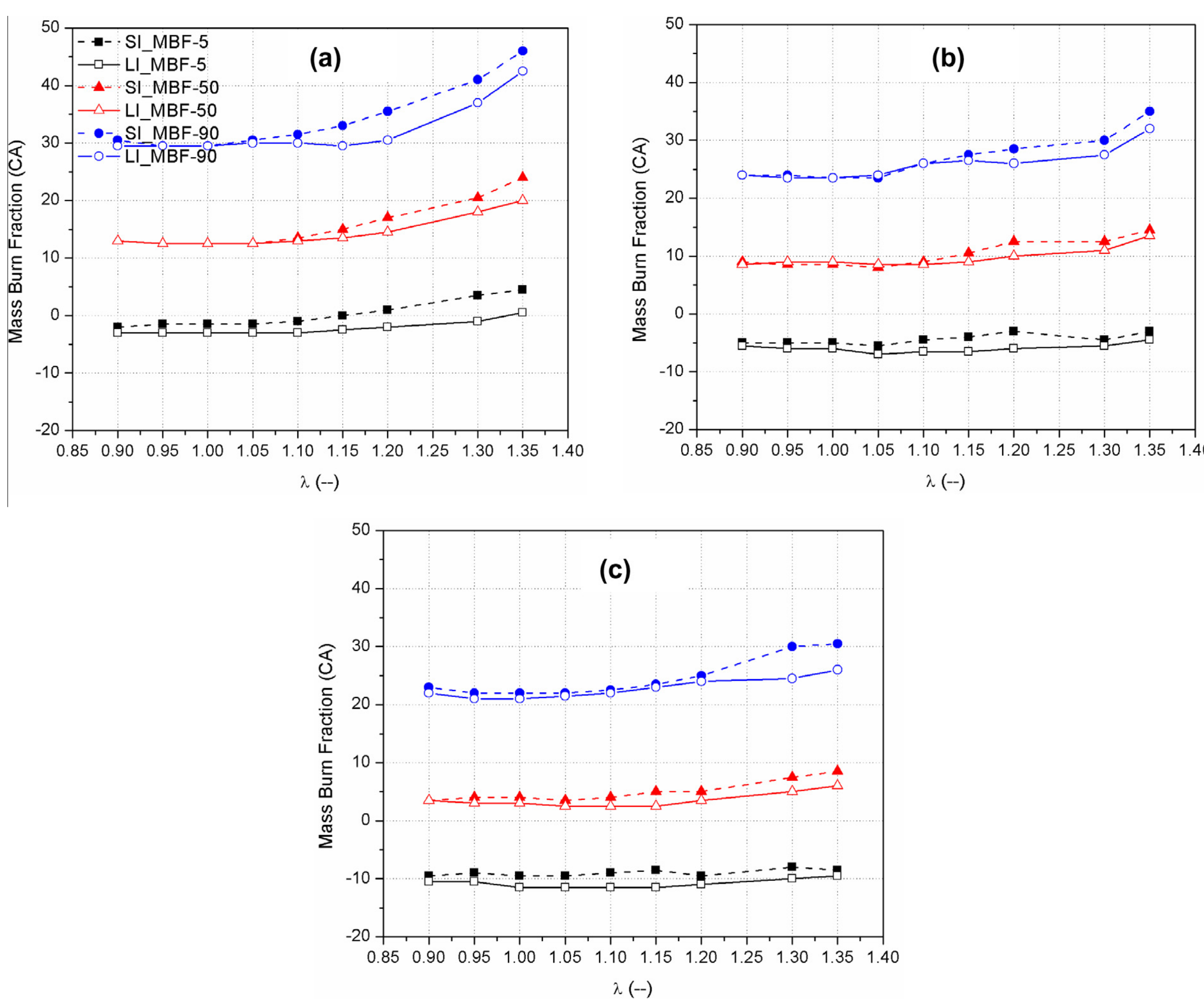

Fig. 4. Comparative variation of 5% MBF, 50% MBF and 90% MBF for SI and LI w.r.t. λ for varying ignition timings (a) 21° BTDC, (b) 25° BTDC, and (c) 29° BTDC.

the interior of the plasma, where it is strongly absorbed at near the focal point [32]. Conventional electrical spark system operates at a frequency below the plasma frequency and sustains the plasma through absorption within a thin layer near the plasma surface [32]. The temperature of laser generated plasma is of the order of 10^6 K and pressure is of the order of 10^3 bar [16,32,33] whereas the temperature and pressure of the plasma generated by conventional electrical spark plug system is of the order of 10^4 K and a few hundred bar respectively [31,34]. Therefore, the laser generated plasma has approximately two orders of magnitude higher temperature and approximately an order of magnitude higher pressure compared to plasma generated by conventional electrical spark plug.

Another difference between the laser ignition and spark ignition is the rate of energy transfer in the plasma. Energy is transferred in nanosecond timescale in laser ignition whereas in spark ignition, it takes place in microsecond timescale. Therefore, as a consequence of higher temperature and pressure and high rate of energy transfer, combustion starts relatively earlier in laser ignition compared to spark ignition. Fig. 5 shows the variation of maximum cylinder pressure w.r.t. λ at three ignition timings for laser ignition and spark ignition. It can be noticed from this figure that maximum cylinder pressure increases with decreasing λ however as the mixture becomes richer beyond stoichiometric, maximum cylinder pressure again decreased. This trend is identical for all ignition timings. Maximum cylinder pressure increased from 29.8 bar to 41 bar, when λ decreased from 1.35 to 1 at ignition timing of 21° BTDC for laser ignition however maximum cylinder pressure decreased to 35.8 bar, when λ further reduced to 0.9. Richer mixtures beyond stoichiometric do not further increase the maximum cylinder pressure because of relatively incomplete combustion. Maximum cylinder pressure also increases for advanced spark timings (spark timings away from the TDC). Higher fuel quantity is combusted relatively earlier with advanced spark timings, before the piston reaches TDC. If the start of combustion is delayed by retarding the spark timing (close to TDC), the maximum cylinder pressure occurs in the later part of the expansion stroke, hence is relatively lower in magnitude. Maximum cylinder pressure was found to be higher for laser ignition compared to spark ignition. Difference in the maximum pressures was significant for leaner mixtures however for $\lambda = 1$ or $\lambda < 1$, maximum cylinder pressure is almost same for both, laser ignition and spark ignition.

Cycle-to-cycle variations in spark ignition engine remains a limiting factor in engine performance, fuel economy and emissions. Due to cycle-to-cycle variations, few cycles give lower combustion efficiency, which adversely impacts overall thermal efficiency as well as emissions. Variability in combustion leads to different work output per cycle, which can be eventually correlated with fluctuations in engine speed and torque, which directly impacts vehicle's drivability. Cyclic variations are a major concern in lean engine operation therefore cycle-to-cycle variability was investigated for laser ignition vis-à-vis spark ignition.

Coefficient of variation (COV) is used to measure the cycle-to-cycle variations in combustion parameters. COV of combustion parameter is calculated using the following equation [31]

$$\mathrm{COV}(X) = \frac{\sigma}{\overline{X}} \times 100\%$$

where $\overline{X}$ is mean of the parameter X and σ is the standard deviation. Cyclic variations are characterized by the COV of indicated mean effective pressure (IMEP) in this study. IMEP is an important and fundamental engine performance parameter, which is extensively used in engine development [31]. Lower COV of IMEP is desirable in order to reduce the cyclic variations and smooth engine operation. Fig. 6 shows the variation in COV of IMEP for laser ignition and spark ignition w.r.t. λ at different ignition timings.

It can be noted from Fig. 6 that COV of IMEP decreases as λ decreases for all ignition timings. Lower COV of IMEP was observed as the ignition timings were advanced from 21° BTDC to 29° BTDC. COV of IMEP was found to be 2.83% and 2.58% respectively for spark ignition and laser ignition at $\lambda = 1.35$ and at 21° BTDC ignition timing. It reduced to 1.16% and 0.83% respectively for spark ignition and laser ignition at the same λ, when ignition timing was advanced from 21° BTDC to 29° BTDC. The rate of reduction in COV of IMEP decreased as the ignition timing was advanced from 21° BTDC to 29° BTDC. COV of IMEP was found to be lower for laser ignition compared to spark ignition. Laser ignition gave lower COV of IMEP for all ignition timings investigated. This indicated that cycle-to-cycle variations in laser ignition are lower compared to spark ignition. This is possibly due to controlled deposition of energy in laser plasma and absence of flame quenching effects in laser ignition.

Effect of laser pulse energy on combustion stability was also investigated. As discussed earlier, there is a difference in energy absorption mechanisms for laser and spark plasma. Chen et al. [35] and Mullett et al. [30] suggested that once plasma is formed, it strongly absorbs the incident laser pulse energy. However, there is certain threshold energy density for a fixed focal volume, beyond which, increased laser pulse energy yields little or no benefit [36]. Therefore for development of future laser ignition systems, it is

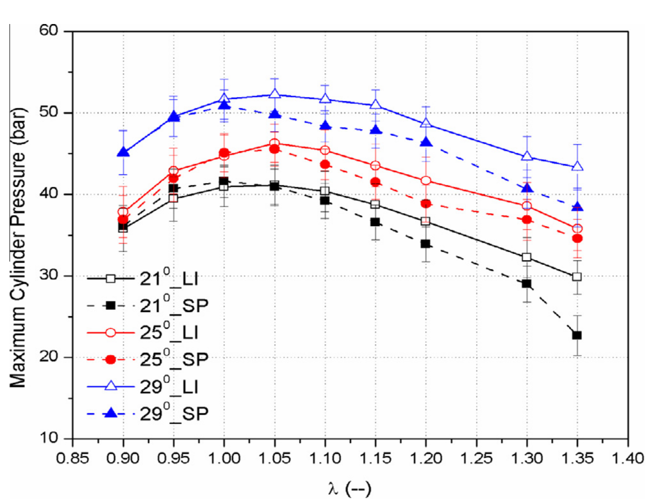

Fig. 5. Maximum cylinder pressure variation w.r.t. λ at different ignition timings.

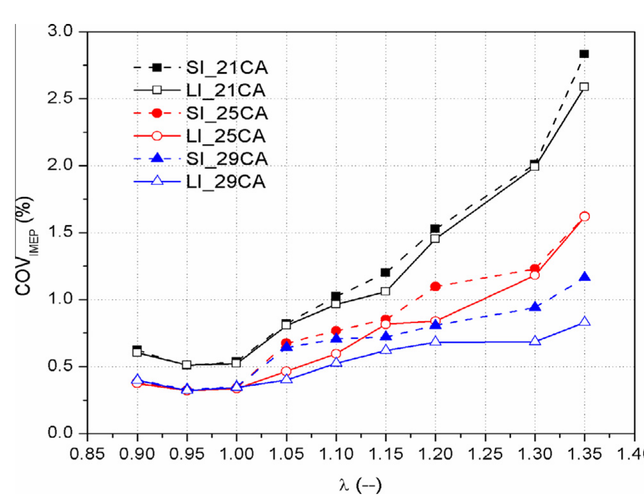

Fig. 6. COV of IMEP for LI vis-à-vis SI w.r.t. λ at ignition timings of (a) 21° BTDC, (b) 25° BTDC, and (c) 29° BTDC.

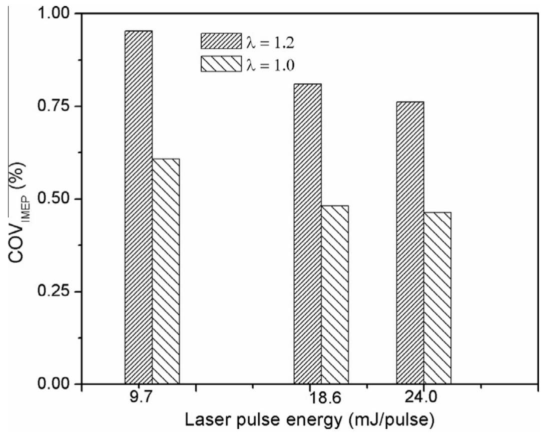

Fig. 7. COV of IMEP for varying laser pulse energy at $\lambda = 1.2$ and $\lambda = 1.0$.

necessary to provide highest possible laser pulse energy in order to achieve superior combustion stability and engine performance. Fig. 7 shows the variation of COV of IMEP with laser pulse energy at $\lambda = 1.2$ and 1.0 at ignition timing of 25° BTDC. COV of IMEP decreases from 0.95 to 0.77 at $\lambda = 1.2$ and 0.6 to 0.46 at $\lambda = 1.0$, when laser pulse energy was increased from 9.7 mJ/pulse to 24 mJ/pulse.

This suggests that greater combustion stability was achieved by increasing laser pulse energy. Enhanced combustion stability with increased laser pulse energy may be due to higher laser energy absorbed by plasma produced inside the combustion chamber, which in-turn leads to increased energy density at the focal point.

After the combustion characterization, comparative engine performance parameters such as brake power (BP) and brake specific fuel consumption (BSFC) of the engine were experimentally evaluated for laser ignition and spark ignition. The power developed by an engine and measured at the output shaft is called BP. BSFC is defined as the mass flow rate of fuel per unit brake power produced. Engine performance is an indicator of engine's ability to convert chemical energy of fuels into useful mechanical power output. Fig. 8 shows the variation of BP and BSFC for laser ignition and spark ignition w.r.t. λ at three ignition timings.

Fig. 8 shows that BP increased with decreasing λ and reached a maxima, before decreasing again w.r.t. decreasing λ. The maximum BP was observed at λ of 1.05, 1.05 and 1.00 respectively for ignition timings of 21° BTDC, 25° BTDC, and 29° BTDC.

For very high λ (lean mixture), heat release and combustion are limited by fuel availability and for low λ (rich mixtures), heat release and combustion are limited by air availability. Because of these two factors, BP first increases with decreasing λ, attains a maxima and then decreases with further reduction in λ. In Fig. 8, BP was observed to be marginally higher for laser ignition compared to spark ignition under almost all experimental conditions. This is attributed to more efficient combustion by laser ignition compared to spark ignition, as it was observed in Fig. 3. BSFC decreased as λ decreased and it reached a minima before increasing again with further reduction in λ. This trend was almost same for all ignition timings investigated. Very high λ leads to low fuel mass flow rate therefore net power output of the engine was also low. Very rich mixtures have high fuel mass flow rate however additional fuel supplied do not really contribute to power output in

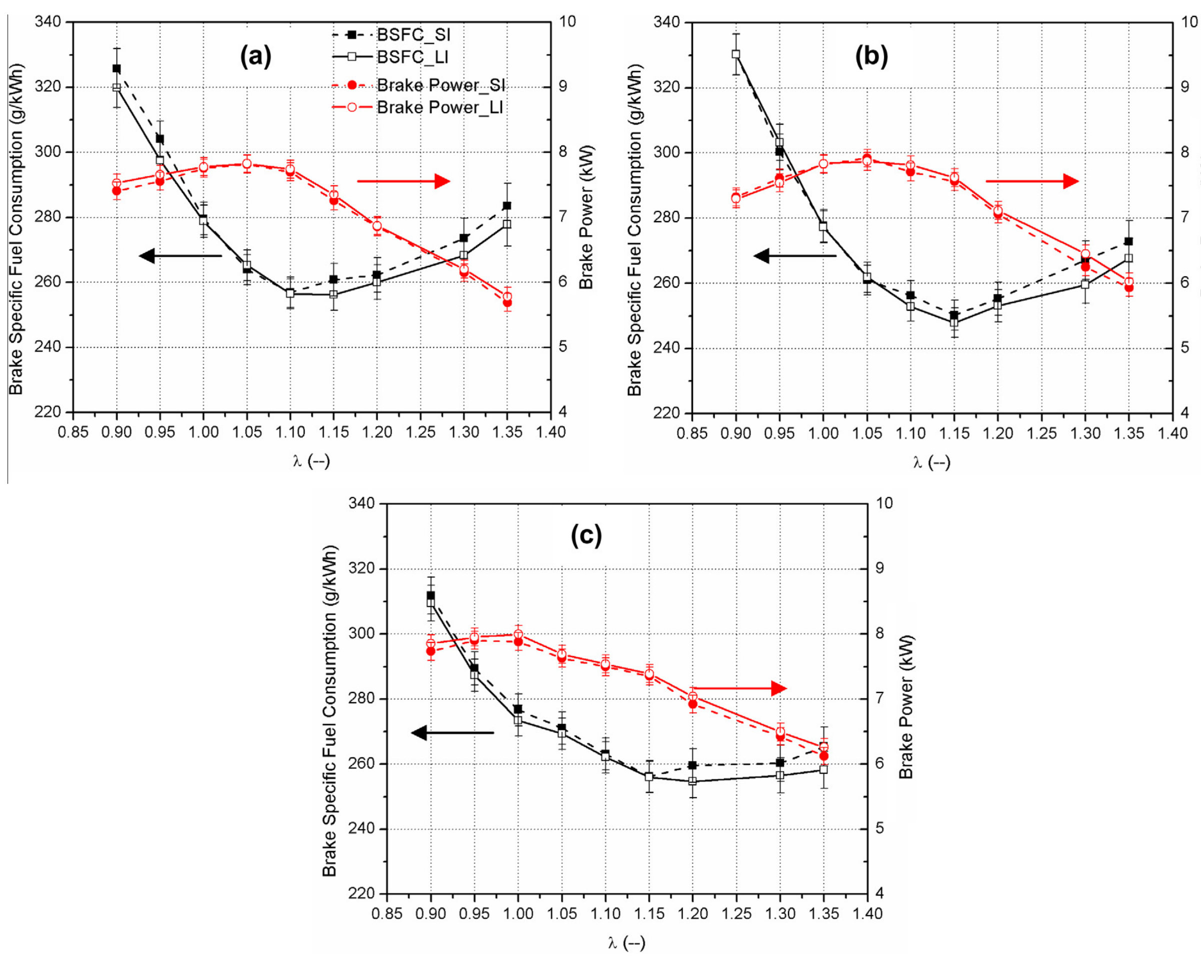

Fig. 8. BSFC and BP for SI and LI initiated combustion w.r.t. λ at ignition timings of (a) 21° BTDC, (b) 25° BTDC, and (c) 29° BTDC.

the same proportion. Because of these factors, BSFC curve has a minima at an intermediate λ. Minimum BSFC is desirable from the engine development point of view. Lowest BSFC was observed at ignition timing of 25° BTDC for both laser ignition and spark ignition. Relatively lower BSFC was seen for laser ignition compared to spark ignition upto $\lambda > 1.10$, however for $\lambda < 1.10$, BSFC was almost same for both laser ignition and spark ignition (Fig. 8b).

Engine out exhaust emissions were compared for laser ignition vis-à-vis spark ignition. Fig. 9 shows the variation of brake specific NOx (BSNOx) and brake specific total hydrocarbon (BSTHC) emissions for laser ignition and spark ignition w.r.t. λ at three ignition timings. Oxides of nitrogen emissions from engine exhaust represent essentially nitric oxide (NO) and nitrogen dioxide (NO_2) collectively known as NOx. Nitric oxide is a major component of NOx emission from spark ignition engines. NO_2 emission contribute only 1–2% in the total NOx emission from SI engine while in diesel engines, contribution of NO_2 in total NOx emission varies from 10% to 30%, depending on load and speed of the engine [31]. Main source of NO formation in the combustion chamber is oxidation of atmospheric nitrogen under high temperature conditions. Another source of NO formation is fuel's nitrogen containing compounds. It can be seen from Fig. 9 that BSNOx increased with decreasing λ and it reached a maxima before decreasing again with further reduction in λ for both laser ignition and spark ignition. This trend was identical for all ignition timings.

NOx formation inside the combustion chamber is highly dependent on the burned gas temperature behind the flame front in a spark ignition engine, where atmospheric nitrogen oxidizes to form oxides of nitrogen. The highest burnt gas temperature is obtained for mixtures slightly richer than stoichiometric but there is very little air present under these operating conditions. On the other hand, as mixture becomes lean, excess air increases but combustion temperature decreases [37]. Therefore, maximum BSNOx emissions were observed at an intermediate λ. Ignition timing has a strong influence on the formation of NOx. Maximum BSNOx increased from approximately 26 g/kW h to 34 g/kW h, when the ignition timing was advanced from 21° BTDC to 29° BTDC. Advanced ignition timing resulted in increase in maximum cylinder pressure and temperature because combustion started relatively earlier and more heat was released before and around TDC. The mixture burning earlier due to advanced ignition timing in the cycle was subjected to higher pressure and temperature due to compression, which remained in these conditions for longer time. Therefore higher NOx was formed upon advancing the ignition timing from 21° BTDC to 29° BTDC. BSNOx emissions were observed to be higher for laser ignition compared to spark ignition upto $\lambda = 1.15$. With further reduction in λ, BSNOx emissions were observed to be almost same for laser ignition and spark ignition. Higher NOx was observed for laser ignition compared to spark ignition possibly because of earlier start of combustion for laser ignition. BSTHC emissions decreased with reduction in λ, reached a minima before increasing again with further reduction in λ for both laser ignition and spark ignition. This trend was almost identical for all tested ignition timings (Fig. 9a–c). Minimum BSTHC was observed for $\lambda = 1.20$, 1.15 and 1.20 for ignition timings of 21° BTDC, 25° BTDC, and 29° BTDC respectively. BSTHC emissions were slightly lower for laser ignition compared to spark ignition, probably because of more efficient combustion.

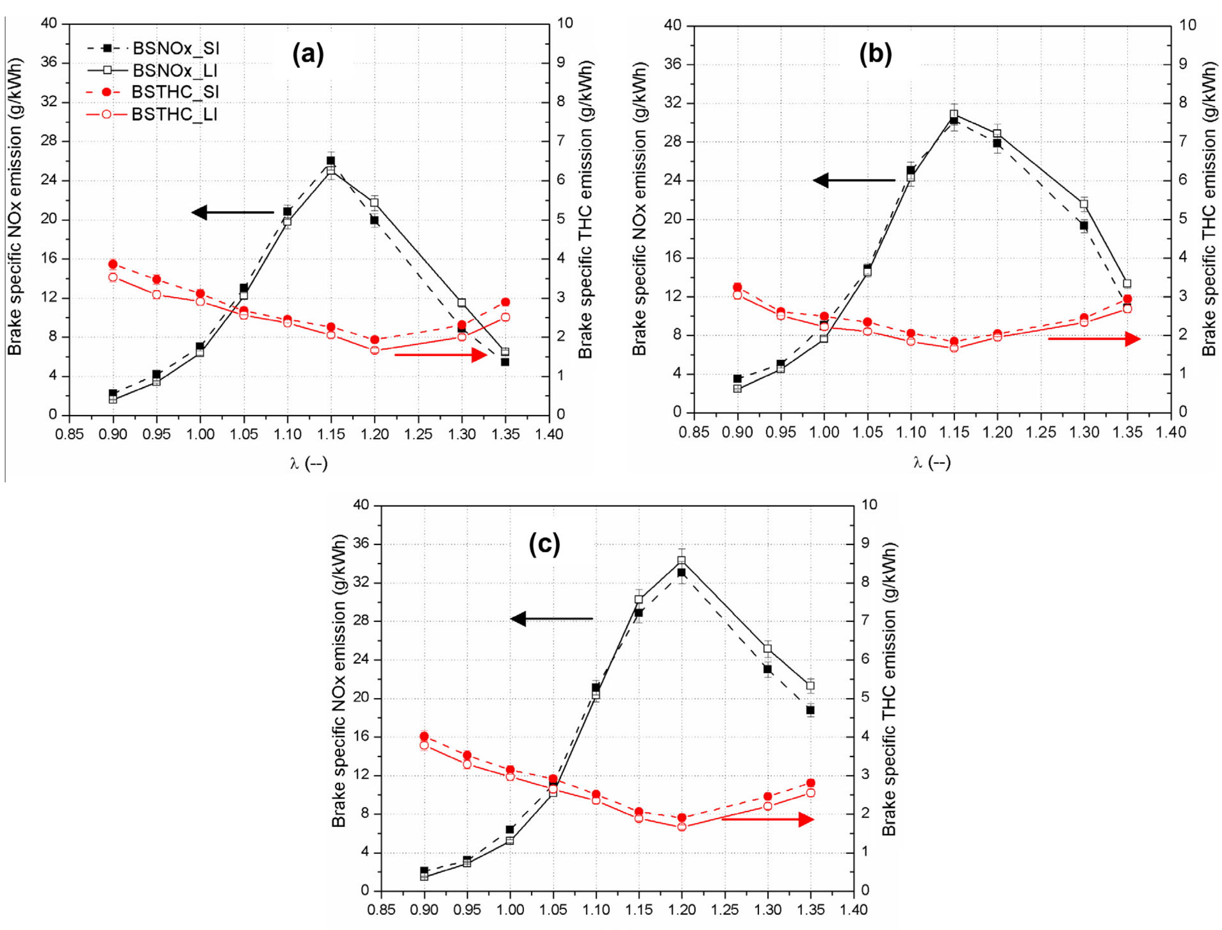

Fig. 9. BSNOx and BSTHC emissions for LI vis-à-vis SI initiated combustion w.r.t. λ at ignition timings of (a) 21° BTDC, (b) 25° BTDC, and (c) 29° BTDC.

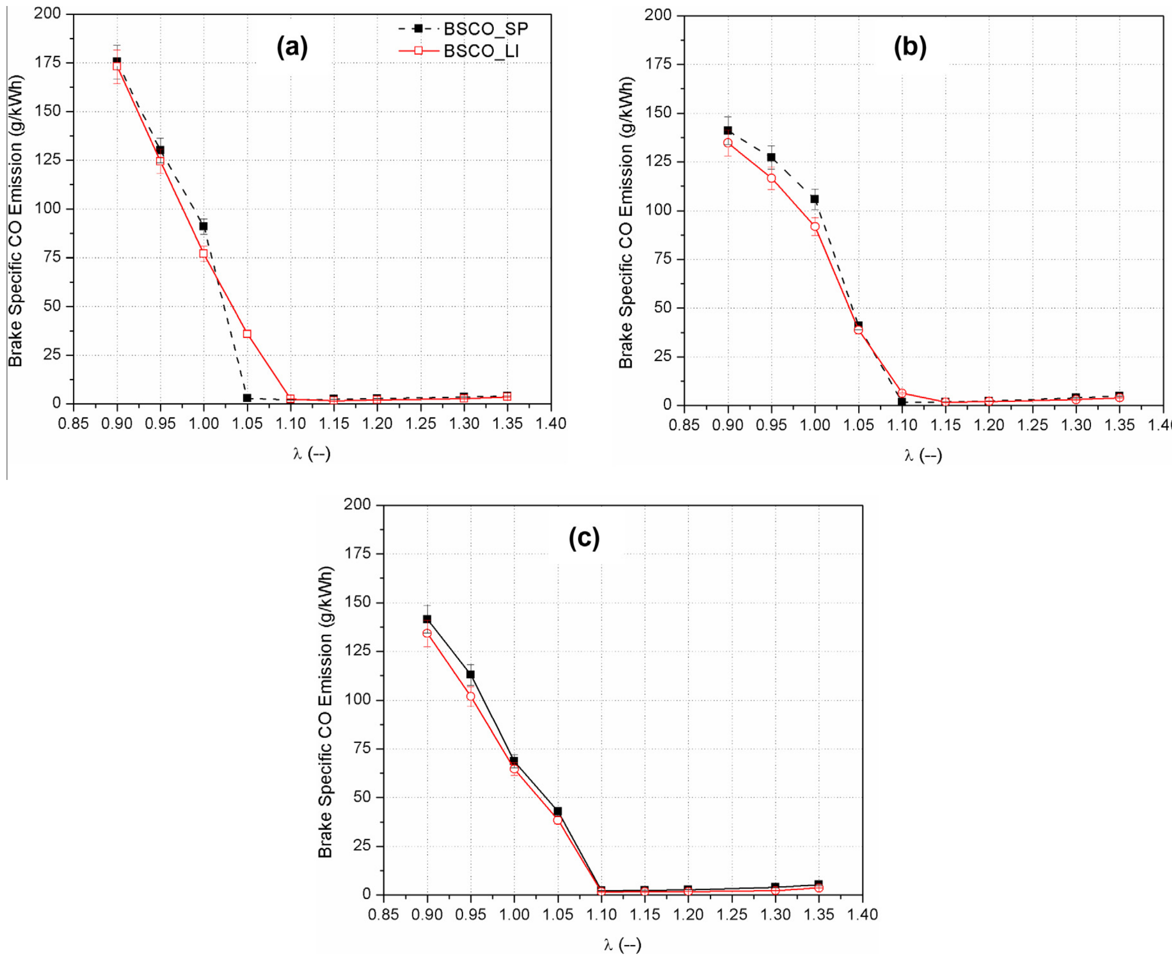

Fig. 10. BSCO emission for LI and SI for ignition timings of (a) 21° BTDC, (b) 25° BTDC, and (c) 29° BTDC.

Fig. 10 shows comparative mass emissions of carbon monoxide (BSCO) for laser ignition and spark ignition w.r.t. λ for different ignition timings. Spark ignition engine often operates on stoichiometric or slightly richer mixtures most of the time in entire engine operating range. CO emission from spark ignition engines are therefore significant. Carbon monoxide emissions are a direct function of λ.

Fig. 10 shows that BSCO emissions are rather small in lean mixtures ($\lambda > 1.1$). For mixture with $\lambda < 1.10$, BSCO emissions increased steadily with reduction in λ. Under lean operating conditions, there was sufficient air available in the combustion chamber to oxidize CO to CO_2 however traces of CO remained in the exhaust due to limited reaction rates. For rich mixtures, CO emissions increased rapidly because of higher degree of incomplete combustion taking place in the combustion chamber. BSCO emissions were lower for laser ignition compared to spark ignition. BSCO emissions were lower in laser ignition compared to spark ignition by ≈11%, 18%, and 28% for $\lambda = 1.35$ at the ignition timings of 21° BTDC, 25° BTDC, and 29° BTDC respectively. This was due to more efficient combustion taking place in laser ignition compared to spark ignition.

4. Conclusions

A comparison of laser ignition and spark ignition systems was carried out in a single cylinder engine for different values of λ and varying ignition timings. On comparison, it was found that maximum cylinder pressure and ROHR were marginally higher for laser ignition compared to spark ignition for same mixture strength and ignition timings. Difference in maximum cylinder pressure between laser ignition and spark ignition decreased, as λ decreased. Higher maximum cylinder pressure and higher ROHR in laser ignition was observed because of earlier start of combustion in case of laser ignition. Combustion advanced in laser ignition in the range of 1–4° CA compared to spark ignition. Cycle-to-cycle variation (COV_{IMEP}) in laser ignition was lower compared to spark ignition. BP was observed to be marginally higher for laser ignition compared to spark ignition. This was attributed to more efficient combustion in laser ignition. Lower BSFC was observed for laser ignition upto $\lambda = 1.10$. After that, BSFC was almost same as that of spark ignition. BSNOx emissions were observed to be higher for laser ignition compared to spark ignition upto $\lambda = 1.15$. With further reduction in λ, BSNOx emissions remained almost identical for spark ignition and laser ignition. BSTHC and BSCO emissions were slightly lower for laser ignition compared to spark ignition.

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