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Effect of laser pulse energy on the laser ignition of compressed natural gas fueled engine

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Abstract. Laser pulses of few a nanoseconds' duration are focused by an appropriate converging lens system, leading to breakdown of the medium (combustible gases), resulting in the formation of intense plasma. Plasma thus induced can be used to initiate the combustion of combustible air-fuel mixtures in a spark ignition engine provided the energy of the plasma spark is high enough. Laser ignition has several advantages over the conventional spark ignition system, especially in case of lean air-fuel mixture. In this study, laser ignition of compressed natural gas was investigated in a constant volume combustion chamber (CVCC) as well as in a single-cylinder engine. Flame kernel visualizations for different pulse energy of natural gas-air mixtures were carried out in the CVCC. The images of the development of early flame kernel stages and its growth with time were recorded by shadowgraphy technique. The effect of laser pulse energy on the engine combustion, performance, and emissions was investigated using different air-fuel mixtures. Increased peak cylinder pressure, higher rate of heat release, faster combustion, and increased combustion stability were observed for higher laser pulse energies. The effect of laser pulse energy on the engine-out emissions was also investigated in this study.
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Keywords: laser ignition; spark ignition; laser pulse energy; plasma; laser irradiance.

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1 Introduction

The ignition system of a spark ignition (SI) engine is responsible for initiating the combustion of air-fuel mixture in the cylinder. For ensuring good performance and efficiency of the engine as well as lower emissions, the spark must be triggered at a precise timing in every engine cycle, which represents the main objective of any ignition system. SI systems have been improved considerably over the years; however, the basic principle remains the same for various ignition techniques. Development of electronic controls to trigger the ignition and use of distributorless ignition systems has made such systems more effective and reliable. However, ignition systems still face serious limitations, such as spark electrode erosion,[1–5] poor performance under high cylinder pressures, total inflexibility in changing the location of ignition point inside the combustion chamber,[6] and large heat losses through the electrodes.[7,8] These limitations need to be tackled in order to develop efficient SI engines for the future.

Stringent exhaust emission norms and demand for higher thermal efficiency can be met by ignition of lean air-fuel mixtures in SI engines. However, lean combustion is associated with slower flame propagation speeds and reduced power output. Engine power output can be improved by increasing initial cylinder pressure by turbo-charging. Increased cylinder pressure, however, requires higher secondary voltage for breakdown of gases to form plasma and initiate combustion in a SI engine using a conventional SI system. Providing required voltage under severe conditions leads to faster spark electrode erosion. Flame speed in lean-burn SI engines can be increased by generating turbulence in the cylinder or by shortening the flame travel path for the same mixture strength.[6] Reduction in flame travel distance can be accomplished by using multiple spark plugs in one cylinder or by placing the ignition point at an optimum location inside the combustion chamber. It is difficult to install multiple spark plugs in multicylinder engines because of the already overcrowded cylinder head. Optimum location of spark inside the combustion chamber is difficult with conventional ignition systems because spark location is always very close to the top of the combustion chamber. There are several types of enhanced ignition systems under consideration, which can be potentially useful in increasing the ignition energy and, hence, the flame speed. These include breakdown ignition systems, Corona ignition systems, plasma jets, rail plug igniters, combustion jets, and laser ignition systems. Experimental evaluation of characteristics, capabilities, and limitations of all these ignition systems was carried out and summarized by Dale et al.[6] Alternative ignition systems have potential to improve the delivery of ignition energy to air-fuel mixtures or allow the ignition energy to be dispersed throughout the combustible charge.[6] However, higher spark energies are also associated with erosion of electrodes, thus shortening the spark plug life span.[6] Furthermore, conventional spark electrodes act as a thermal energy/heat sink because spark plasma energy is actually liberated between its two metallic electrodes. A durable, high-energy, electrode-less ignition system with controlled energy deposition in the plasma, having flexibility to change the ignition location, is, therefore, a desirable option for overcoming these limitations in a lean-mixture fueled SI engine. A laser ignition system,

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which meets most of these requirements, also offers potential advantages for igniting lean mixtures.

Lasers are emerging as strong contender for an alternative ignition source of SI engines. Short laser pulses of a few nanoseconds' duration delivered by a Q-switched laser can be focused by an appropriate converging lens system inside the combustion chamber containing combustible mixture. If the peak intensity in the focal region exceeds threshold intensity level, breakdown of the medium (combustible gases) occurs, leading to formation of plasma as shown in Fig. 1.

If the energy content of the spark is high enough, the mixture ignites. Laser-induced plasma is generally more compact and has a higher maximum temperature than other continuous-arc sources.[9–11] Plasma induced this way can be used to initiate the combustion of air-fuel mixtures in SI engines.

There are several potential benefits of laser ignition over conventional spark ignition. Advantages of laser ignition were reviewed by Paul.[12] The laser ignition system is free from electrodes; hence, there is no loss of spark energy/plasma heat to the electrodes unlike in a conventional electrical spark ignition system. Since the laser ignition system does not employ any spark electrode, there is no electrode erosion effect, as observed in case of spark plugs; therefore, the life span of a laser ignition system is expected to be significantly longer than that of a spark plug system.[13] On the other hand, in case of laser ignition, minimum pulse energy required for ignition decreased with increasing gas pressure (p) due to pressure dependence of nonresonant breakdown. This is opposite to conventional electrical spark ignition systems, which require higher energy with increasing gas pressure.[14] This turns out to be one of the main attractive points for laser ignition. The ignition initiator spark can be placed at an optimum location inside the combustion chamber using a suitable focal length of the converging lens or by changing the position of the converging lens in the optical spark plug. This way, flame propagation distance can be shortened and combustion duration can be reduced. Further, multipoint ignition can also be realized more easily (according to required space, e.g., by multiple sparks) out of adaptive optics using a laser ignition system. There are, however, several challenges of laser ignition as well. The cost of laser ignition systems, propagation of a laser beam from the laser head to the combustion chamber, and durability of the optical window, through which the laser beam is guided into the combustion chamber, are some of the challenges that need to be addressed.

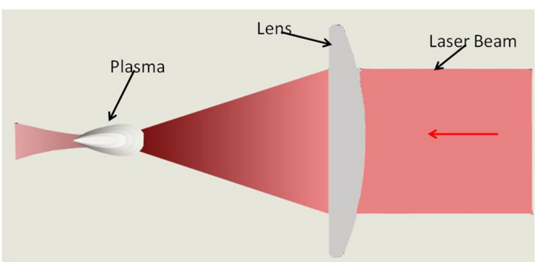

Fig. 1 Laser-induced plasma formation (laser is propagating from right to left).

Combustion behavior of laser ignition in simulated engine conditions was investigated by several researchers.[15–23] In most of these studies, a constant volume combustion chamber (CVCC) was used to simulate engine conditions (end of the compression stroke conditions, except turbulence). Several operating variables, such as laser and optics parameters, minimum ignition energy, etc., were varied and their effect on rate of pressure rise, ignition delay, etc., were experimentally evaluated for different fuels in these studies. These experiments were very helpful in developing technical feasibility of the concept of laser ignition for internal combustion (IC) engines. Laser ignition of IC engines was first demonstrated by Dale et al.[24] in 1978. Results obtained from laser ignition were then compared with conventional spark ignition systems. A higher rate of pressure rise was observed with laser ignition using 300 mJ laser pulse energy. The lean limit of air-fuel ratio was successfully extended from 22.5:1 to 27.8:1 for laser ignition.[24] Bihari et al.[25] compared laser ignition and conventional spark ignition in a single-cylinder research engine fueled with compressed natural gas (CNG). It was reported that due to laser ignition, the lean misfire limit extended from an equivalence ratio of 0.55 to 0.50. Combustion stability also improved for retarded ignition timings. Because of these two reasons, ~50% NOx reduction was observed with laser ignition. Herdin et al.[26] carried out experiments of laser ignition on a large-bore natural gas fueled engine. They reported that the energy required for producing plasma decreased with increasing in-cylinder pressure, as theoretically expected. Therefore, higher charge density in the combustion chamber is a favorable condition for laser ignition as opposed to electrical spark ignition. McMillian et al.[27] performed laser ignition and results were compared with a conventional spark plug delivering ~68 mJ/spark. Laser ignition energy (~50 mJ/spark) was kept constant during the experiments. With laser ignition, the total operating envelope of the engine was defined as the area between knock and misfire limits, and this operating envelope increased by 46% compared to a conventional spark ignition system. NOx emissions reduced by ~50% for laser ignition, and the hydrocarbon emissions were comparable for both ignition systems. Ignition delay was also found to be shorter for laser ignition compared to the conventional SI system. Mullett et al.[28] investigated the effect of laser parameters, such as laser pulse energy, beam quality, minimum beam waist size, and focal length of the converging lens, on the engine combustion, performance, and stability of combustion for stoichiometric gasoline-air mixture. Minimum ignition energy and minimum energy required for breakdown of air were found to increase with increasing focal length of the converging lens and the aperture diameter. It was found that greater combustion stability was achieved for higher laser pulse energies. Graf et al.[29] and Srivastava and Agarwal[30] investigated optimum ignition location inside the combustion chamber by moving the location of converging lens to cover almost entire length of the combustion chamber. The lowest specific fuel consumption was found when plasma (ignition location) was placed at the center of the combustion chamber. Thus, laser ignition was useful in extending the lean limit of air-fuel mixture, thereby reducing the NOx emissions.

Full benefits of laser ignition can be realized only by optimizing various parameters, including focal length of the converging lens, laser pulse energy, beam profile, in-cylinder pressure, fuel-air equivalence ratio, plasma position inside the combustion chamber, plasma spark size, permissible turbulence, etc. Laser pulse energy is a very important parameter in laser ignition. It is necessary to evaluate the engine performance with varying laser pulse energy in order to optimize the laser for engine applications. Cost of a laser system is a function of maximum laser pulse energy. Therefore, in this study, laser pulse energy was varied, and its effect on engine performance, combustion, and emissions in a CNG gas-fueled engine were investigated.

2 Experimental Setup

Laser ignition of combustible air-fuel mixtures was first investigated in a CVCC. Details of the experimental design can be found in Ref. 22. All experiments were conducted at 10-bar initial chamber pressures and 373-K chamber temperature. A converging lens of 100-mm focal length was used to focus the laser beam to a point inside the CVCC. Minimum laser ignition pulse energy was measured for different relative air-fuel ratios (λ) at 10-bar initial chamber filling pressure. Pressure–time history of the CVCC was recorded for minimum ignition energy and higher ignition pulse energy. Flame kernel development of the combustible air-fuel mixture was investigated under different λ values using high-speed camera operating at 54,000 fps, and the captured images were interrogated for temporal propagation of the flame front.

After investigating the effect of laser pulse energy on pressure rise and flame kernel development in the CVCC, laser ignition was done in a single-cylinder engine. The engine was coupled with an eddy current dynamometer. Engine speed and load were controlled by varying the excitation current of the eddy current dynamometer. The dynamometer was also connected to a three-phase electric motor, which was engaged to start the engine using a gear box and was disconnected, once the engine was fired. CNG was used as test fuel in the experiment. Since CNG is stored at very high pressure ($\sim$225 bar), a pressure reducer was used to bring the fuel pressure down to 1 bar for the experiment. Reduced-pressure fuel line was connected immediately upstream of throttle in the air intake system. A laminar flow element (LFE) (Meriam, 50MC2-2F) was installed for the intake air flow rate measurement. LFE was connected to an inclined manometer, which measured the pressure drop across the orifice of the LFE. For monitoring the in-cylinder pressure variations during an engine cycle, a piezoelectric pressure transducer (Kistler, 6013C) was mounted flush with the cylinder head. Signals from the pressure transducer were amplified and converted to voltage signals by a charge amplifier (Kistler, 5015), which were finally acquired by a high-speed combustion data acquisition system (HI-Techniques, meDAQ). Exhaust emissions were measured using a raw exhaust gas emission analyzer (Horiba, EXSA-1500). After setting each operating variable of the engine, measurements were taken after ensuring the engine's thermal stabilization.

A flash lamp pumped Q-switched Nd:YAG laser (Litron, Nano L-200-30) was used for ignition of combustible fuel-air mixture. This laser delivered pulse energy up to 200 mJ with a pulse duration of 6 to 9 ns at FWHM at the fundamental wavelength (1064 nm). The beam diameter was 5 mm ($1/e^2$). Maximum repetition rate of the laser was 30 Hz. To enhance the laser beam quality and beam profile and, thereby, to reduce the beam quality factor M^2, an aperture of diameter 2.9 mm was inserted between the safety shutter and the output mirror of the laser. This led to improvement in M^2 value but it reduced the maximum output pulse energy as well. Laser pulse energy can also be changed by changing the flash lamp voltage; however, this also leads to changes in laser parameters, such as spatial beam profile, and pulse duration. In this investigation, laser pulse energy was varied continuously by an external wave plate/polarizer installed ahead of laser, keeping the flash lamp voltage at the maximum so that the spatial beam profile remains identical during the entire experiments. The energy of each pulse was measured using a pyroelectric detector (Coherent) and a laser energy meter (Coherent). A laser spark plug was designed, manufactured, and installed in the cylinder head in place of the conventional spark plug (Fig. 2). The laser spark plug consists of two parts: (1) a window holder and (2) a lens holder. The lens cannot withstand harsh environment prevailing in the combustion chamber at the time of combustion, with extremely high pressure and temperature. Therefore, a sapphire window (thickness = 3 mm, diameter = 12.5 mm) was used to seal the combustion gas leakages and to transmit the laser beam without being affected by the harsh environment. The clear aperture of the window was $\sim$8 mm for this experiment. The plasma location inside the combustion chamber can be changed by rotating the lens holder inside the window holder. A lens of 30-mm focal length was used to focus the laser in the combustion chamber and to create plasma. Plasma location was kept the same as that of the conventional spark plug system. An electronic circuit was designed to synchronize the laser with the engine. This circuit was used to trigger the laser at a specified crank angle position, i.e., at a particular ignition timing in each engine cycle.

The laser beam propagated in air from the laser head to the laser spark plug. The laser beam passed through a collimating unit comprising diverging and focusing optics. The beam first enlarged to form a parallel beam of larger diameter. This beam was then reflected by a reflector into the laser spark plug. The laser beam was finally converged and focused tightly in the cylinder head using a converging lens and a window, and finally plasma formation took place. The optical path of the laser beam in the engine investigations is shown in Fig. 3.

Fig. 2 Laser spark plug installed in the cylinder head.

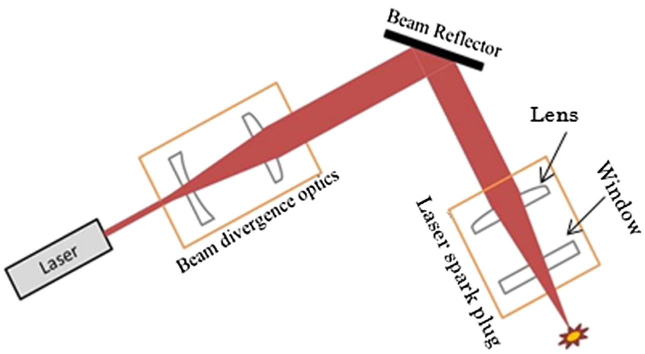

Fig. 3 Optical beam path for the engine experiments.

All experiments were carried out on a naturally aspirated, water-cooled, four-stroke single-cylinder engine running at constant engine speed (1500 rpm) under wide-open throttle condition. Laser ignition was performed for two different relative air-fuel ratio (λ) mixtures: (1) a lean mixture ($\lambda = 1.2$) and (2) a stoichiometric mixture ($\lambda = 1.0$). Spark timing was fixed at 25 deg crank angle before top dead center (CA BTDC) for the experiment. Laser pulse energy was varied from 9.7 to 24 mJ/pulse, and its effect on various engine combustion, performance, and emission parameters is discussed in the following section.

3 Results and Discussion

Experiments were conducted to evaluate the pressure–time history in the CVCC for laser ignition of combustible mixtures with varying air-fuel ratios (λ). The minimum pulse energy required for ignition under different experimental conditions was experimentally determined. Minimum laser pulse energy required to ignite different combustible mixtures at 10 bar chamber filling pressures are given in Table 1. Minimum ignition energy increased with increasing λ. For leaner mixtures, the number of fuel molecules in the focal spot volume is lower for the same focal length of converging lens. Hence, radicals responsible for combustion are also produced in lesser numbers.[14] Therefore, higher laser pulse energy is required to ignite leaner combustible fuel-air mixtures.

To determine the effect of laser pulse energy, experiments were conducted at a higher laser pulse energy compared to the minimum energy required for ignition at 10-bar chamber filling pressures for different λ values, without changing the optics. Figure 4 shows the comparative pressure-time history of the CVCC for different laser pulse energies. In Fig. 4, thick pressure lines denote higher ignition energy and thin pressure lines denote minimum ignition energy.

Table 1 Minimum laser pulse energy required for ignition of combustible mixtures at 10-bar initial chamber filling pressure. Focal length of lens = 100 mm.

Relative air-fuel ratio (λ)	Minimum laser pulse energy required for ignition (mJ/pulse)
1.1	9.6
1.2	9.6
1.3	9.6
1.4	9.6
1.5	10.2
1.6	10.7

Experiments were conducted for higher laser pulse energy (12.5 mJ/pulse) compared to minimum ignition pulse energy required for ignition. Slightly higher maximum pressures and relatively shorter combustion duration were observed with higher ignition energy compared to minimum ignition energy. Since the experiments were done using a fixed converging lens (focal length 100 mm), increasing ignition pulse energy increased the laser irradiance at the focal point. This enhances the flame velocity and reduces the combustion duration.

To verify the effect of laser pulse energy on the flame propagation, temporal variations of flame kernel development in the direction opposite to laser propagation (X-direction) and in the direction orthogonal to laser propagation (Y-direction) were calculated from the acquired shadowgraphs of the flame kernel for minimum and higher ignition pulse energies. Flame kernel visualizations for different λ values of natural gas-air mixtures were carried out in the CVCC. The images of the development of early flame kernel stages and its growth with time were recorded by shadowgraphy technique. These images provided useful information about the flame kernel development and the shape of the flame kernel as a function of time. Figure 5 shows typical structure of the flame kernel.

Based on these observations, the shape of the laser-induced flame kernel can be thought to be having two stages of development. In early stage of flame kernel development, the kernel develops radially to form a toroidal shape.[27] In the latter stage of development, a front lobe is formed, which propagates backward toward incoming laser beam.[27–30] Temporal variation of flame kernel development in various directions with time inside the CVCC was analyzed for varying λ. This information can be obtained by analyzing

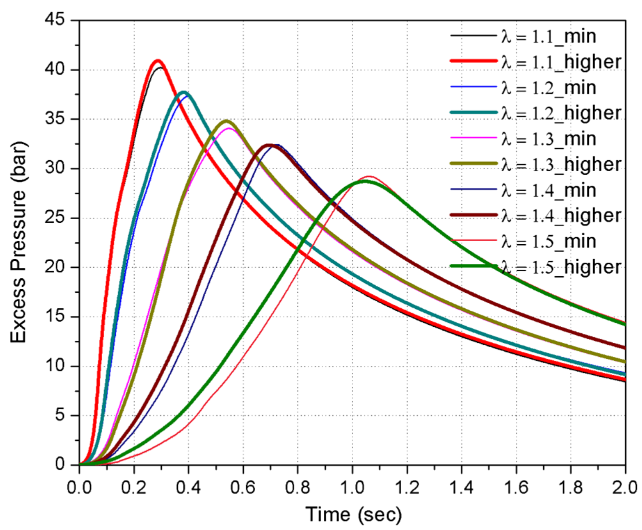

Fig. 4 Comparative constant volume combustion chamber pressure-time history for two different laser pulse energies at initial chamber filling pressure of 10 bar (minimum ignition energy at specified λ and 12.5 mJ/pulse laser energy).

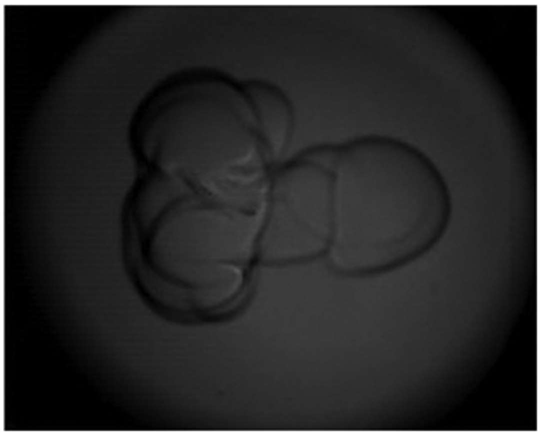

Fig. 5 Typical shape of flame kernel created by laser ignition ($\lambda = 1.2$).

different shadowgraphs captured by the high-speed camera. The laser's direction of propagation is taken as $X+$ and the direction opposite to the laser propagation is taken as $X-$, which is also the direction of propagation of the front lobe. Centroid of the first kernel was taken as origin for calculating distance in the three directions ($X+$, $X-$, and Y). Temporal variation of flame kernel is presented in the next section.

X-direction is the direction of propagation of the front lobe of the flame kernel. Temporal variation of flame kernel is shown in Fig. 6 for different λ values at 10-bar initial chamber filling pressure. It can be seen from Fig. 6 that at the same λ, front lobe propagation (X-direction) and toroidal radius propagation (Y-direction) were higher for higher ignition pulse energy compared to minimum ignition pulse energy.

The front lobe grew at a faster rate with higher ignition pulse energy compared to minimum ignition pulse energy.

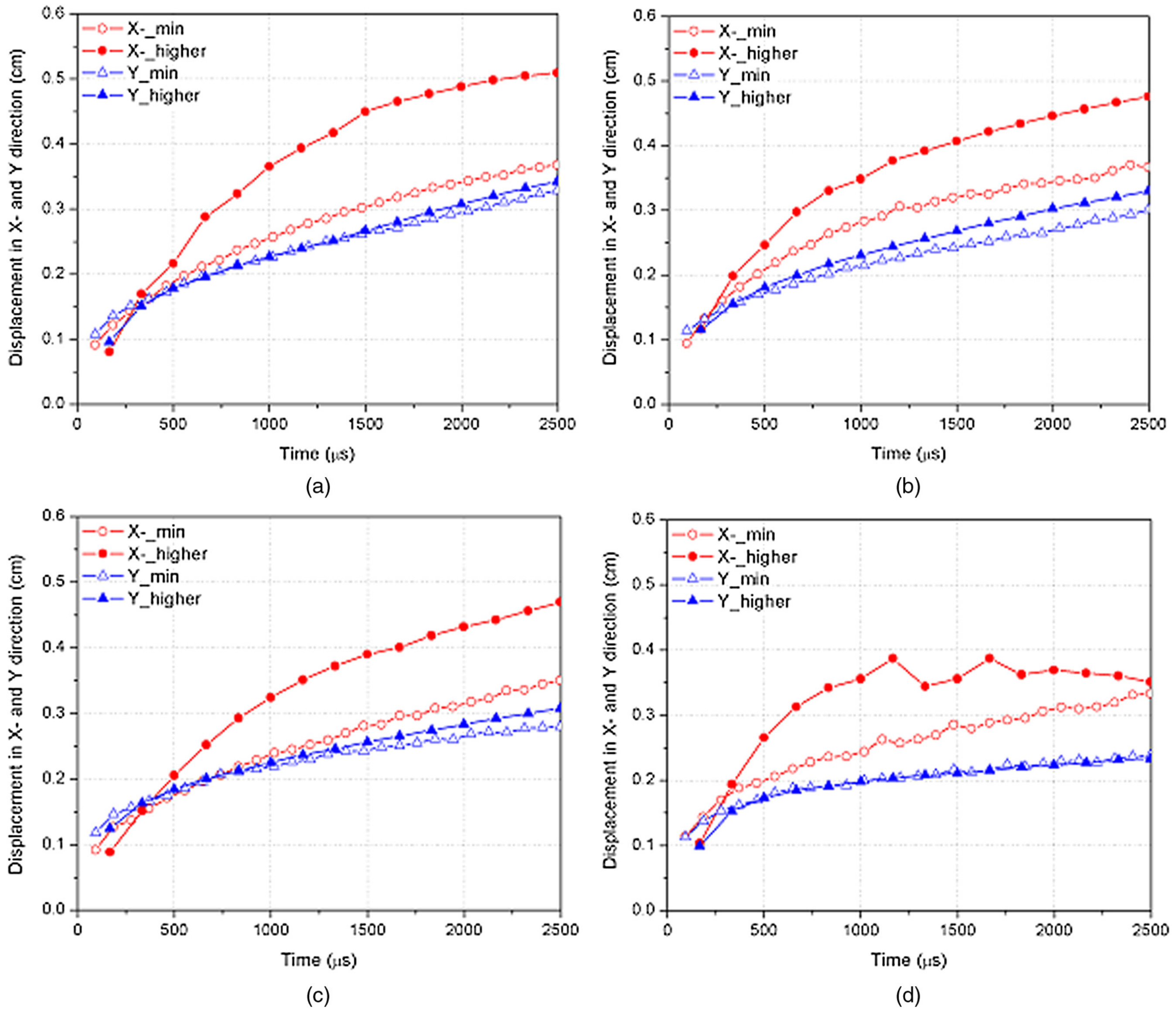

Fig. 6 Temporal variation of flame kernel development in the direction opposite to laser beam propagation (X-direction) and orthogonal to the laser beam propagation (Y-direction) for (a) $\lambda = 1.2$, (b) $\lambda = 1.3$, (c) $\lambda = 1.4$, and (d) $\lambda = 1.5$ at 10-bar initial chamber filling pressure.

Front lobe propagation distance was 0.48 cm with higher ignition energy, whereas it was 0.34 cm with minimum ignition pulse energy for $\lambda = 1.2$ after 2000 μs. At higher laser pulse energy, more photons interact with gas molecules per unit volume; therefore, more molecules are available for multiphoton ionization, which gave rise to more electrons. The collision frequency between these electrons and gas molecules rises, thus accelerating ionization of gas molecules. Hence, the time for electron avalanche and gas breakdown is shortened and ignition strength reinforced. This leads to higher temperature and pressure of the flame kernel and acceleration of the flame front.[31]

Effect of laser pulse energy was then investigated to assess the performance of laser ignition and its effect on engine combustion, performance, and emissions. Laser pulse energy was varied by external beam energy attenuator keeping the flash lamp voltage at the maximum. Laser pulse energy was varied from 9.7 to 24 mJ/pulse. This energy was measured after incorporating all losses taking place at the lenses and the window. Therefore, this is the energy that is finally available inside the engine combustion chamber for plasma formation and ignition of combustible mixture. Minimum pulse energy for ignition at this operating condition of the engine was 8.5 mJ/pulse for both λ values. Maximum pulse energy of laser with 2.9-mm-diameter aperture was 24 mJ/pulse. That is why, laser pulse energy was varied from slightly above the minimum laser ignition energy to the maximum available laser pulse energy. A converging lens of 30-mm focal length was used to focus the laser into the engine cylinder in order to produce plasma. Experiments were performed at fixed ignition timing of 25-deg BTDC and two different values of λ (lean mixture with $\lambda = 1.2$ and stoichiometric mixture with $\lambda = 1.0$).

Figure 7 shows the variation of cylinder pressure and rate of heat release (ROHR) with crank angle for three different laser pulse energies: 9.7, 18.6, and 24 mJ/pulse. Cylinder pressure and ROHR curves in this figure are an average of 100 consecutive engine cycles. This is done in order to reduce the effect of cyclic variations. It can be seen from Fig. 7 that maximum cylinder pressure and maximum ROHR increase slightly with increase in laser pulse energy. Maximum cylinder pressure increased from 40.5 to 42.1 bar for $\lambda = 1.2$ and from 44 to 46 bar for $\lambda = 1.0$, when the laser pulse energy was increased from 9.7 to 24 mJ/pulse. Crank angle position of maximum cylinder pressure also shifted by 1 deg toward TDC. This indicated that maximum cylinder pressure and rate of the pressure rise increased upon increasing the laser pulse energy. The effect of laser pulse energy on pressure rise in the CVCC also followed the same behavior as the engine.

Maximum ROHR increased from 68.7 to 69.8 J/deg at $\lambda = 1.2$ and from 77.6 to 80 J/deg at $\lambda = 1.0$, when the laser pulse energy was increased from 9.7 to 24 mJ/pulse. Crank angle position of maximum ROHR also shifted from 7.5 deg after top dead center (ATDC) to 6.5 deg ATDC at $\lambda = 1.2$ and from 7 deg ATDC to 5.5 deg ATDC for $\lambda = 1.0$. Increase in maximum cylinder pressure and ROHR with increasing laser pulse energy may be attributed to an earlier start of combustion. Mass burn fractions (MBFs) of 5, 50, and 90% were calculated (Fig. 8) for all laser pulse energies tested to clearly observe this effect.

MBF of 5% occurred at 5.5- and 6.5-deg BTDC with laser pulse energy of 9.7 and 24 mJ/pulse, respectively, at $\lambda = 1.2$. Therefore, ignition delay was seen to decrease with increasing laser pulse energy, which leads to difference in maximum cylinder pressure and ROHR, as observed in Fig. 7. Timing of 50% MBF and end of combustion (90% MBF) also retarded with increasing laser pulse energy.

Laser irradiance and focal spot size at the focal point is an important parameter, which governs combustion behavior and combustion stability in the laser ignition.[31] Laser irradiance (W/cm^2) is defined as the laser power divided by the area of the focal spot. The diameter of the focal spot produced by the focusing lens can be calculated by the procedure elaborated by Steen[32]

$$D = \frac{4f\lambda}{\pi d} M^2.$$

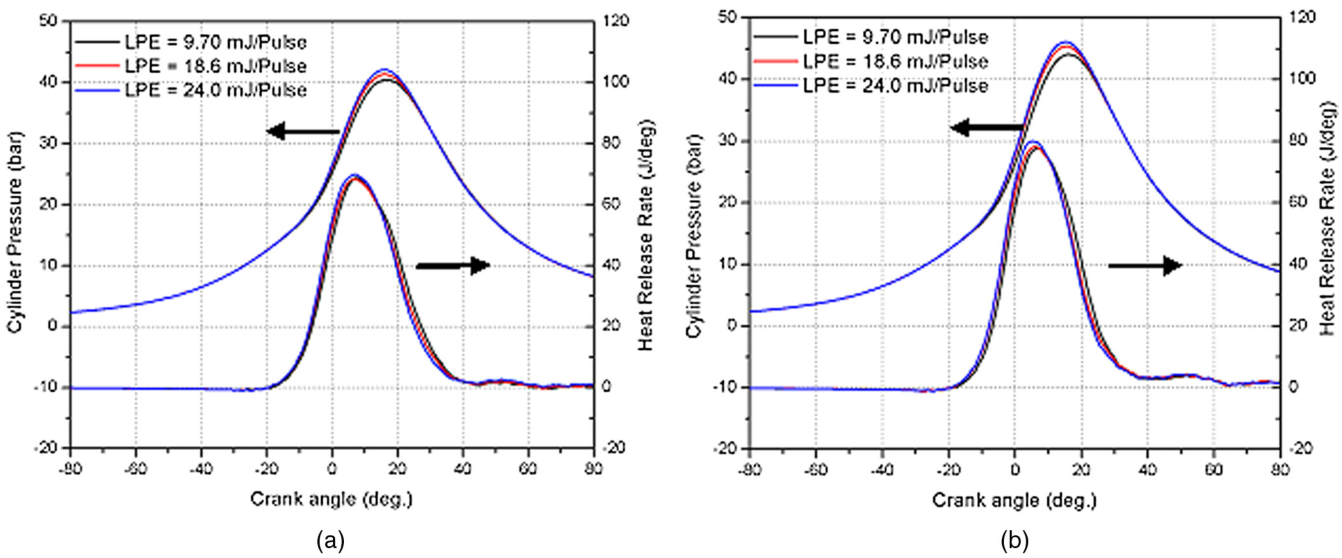

Fig. 7 Cylinder pressure and rate of heat release variations with crank angle for different laser pulse energies at (a) $\lambda = 1.2$ and (b) $\lambda = 1.0$.

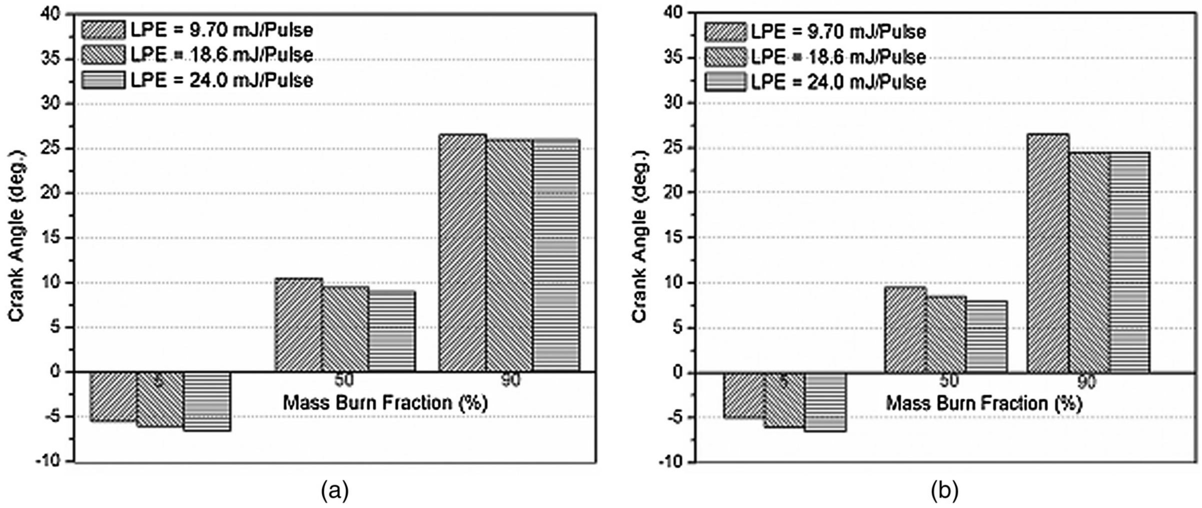

Fig. 8 Mass burn fraction variation for different laser pulse energies at (a) $\lambda = 1.2$ and (b) $\lambda = 1.0$.

Here, D is the diameter of the focal spot, f is the focal length of the converging lens, λ is the wavelength of the laser beam, d is the diameter of the laser beam at the converging lens, and M^2 is the beam quality factor. This formula was derived by neglecting the spherical aberrations of the lens. For a fixed focal length of the converging lens (30 mm), focal point size is constant (41.3 μm). Laser irradiance will, therefore, be higher for higher laser pulse energy. Laser irradiance at the focal point increases from 1.2×10^{11} to 3.0×10^{11} $\mathrm{W/cm^2}$ with increase in laser pulse energy from 9.7 to 24 mJ/pulse. Higher laser irradiance leads to relatively earlier combustion and shorter ignition delay.

Cyclic variations are a major concern in lean-burn engine operation; therefore, cycle-to-cycle variability was investigated. Cyclic variations are characterized by the coefficient of variation (COV) of the indicated mean effective pressure (IMEP). IMEP is an important and fundamental engine parameter that is used extensively for engine development.[33] Figure 9 shows the variation in COV of IMEP with laser pulse energy at $\lambda = 1.2$ and 1.0. COV of IMEP decreased from 0.95 to 0.77 at $\lambda = 1.2$ and from 0.6 to 0.46 at $\lambda = 1.0$, when the laser pulse energy was increased from 9.7 to 24 mJ/pulse.

This suggests that greater combustion stability is achieved by increasing laser pulse energy. Enhanced combustion stability with increased laser pulse energy may be due to greater fraction of laser energy absorbed by the plasma produced inside the combustion chamber, which in turn leads to increased laser irradiance at the focal point. Chen et al.[34] and Mullett et al.[28] suggested that once plasma is formed, it becomes a strong absorber of the incident laser pulse energy. However, there is certain threshold laser irradiance for a fixed focal volume, beyond which, increased laser pulse energy yields little or no benefit.[31] Therefore, for future laser ignition systems, it is necessary to provide the highest possible laser pulse energy in order to achieve superior combustion stability and engine performance. Excessive laser pulse energy may also damage the piston because excess laser pulse energy can be transmitted through the cylinder gases and plasma and consecutively hit the piston surface,

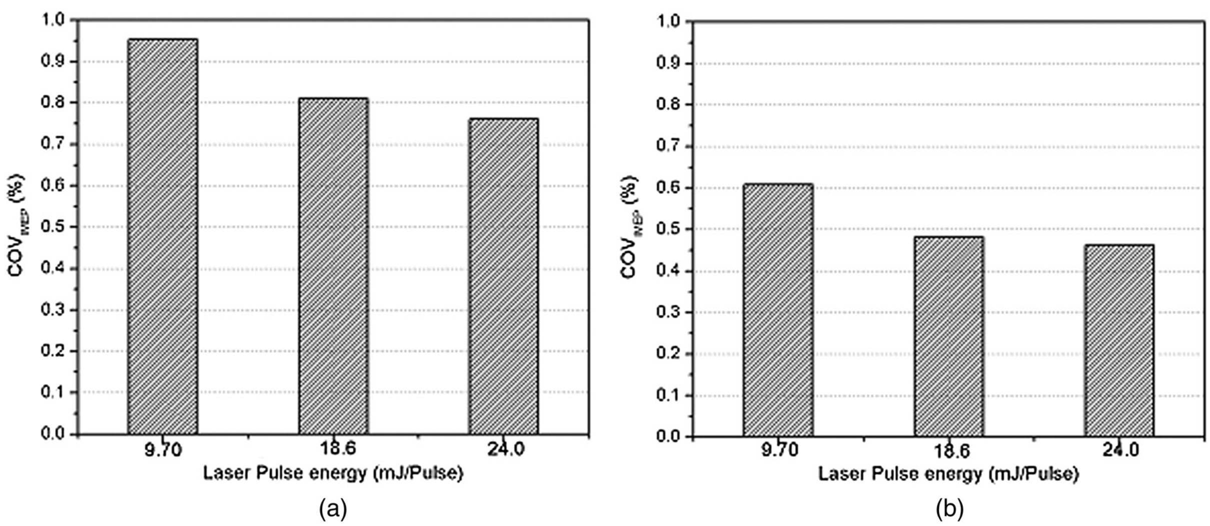

Fig. 9 Coefficient of variation of indicated mean effective pressure for varying laser pulse energy at (a) $\lambda = 1.2$ and (b) $\lambda = 1.0$.

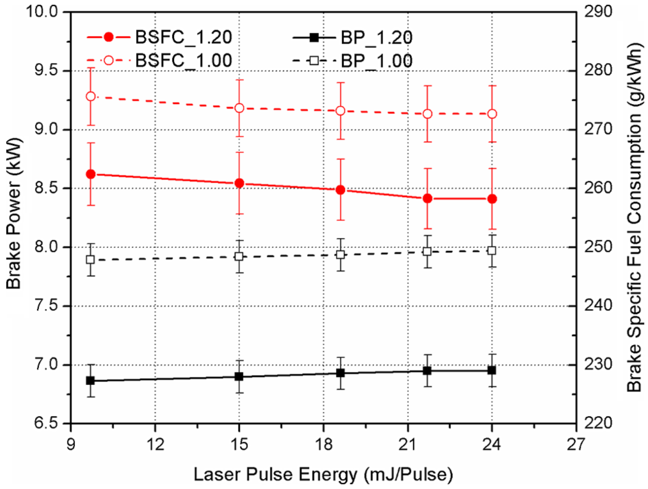

Fig. 10 Brake power and brake-specific fuel consumption variations with respect to laser pulse energy for $\lambda = 1.2$ and $\lambda = 1.0$.

thereby damaging it. Laser irradiance at the piston surface depends on several factors, such as position of the piston at the time of laser firing, focal length of the converging lens, beam quality, laser pulse energy, etc. However, any damage to the piston surface was not observed in the present experiment, where laser pulse energy was increased from 9.7 to 24 mJ/pulse.

After combustion investigations, engine performance and exhaust emissions were investigated for varying laser pulse energy. Figure 10 shows the brake power (BP) and brake-specific fuel consumption (BSFC) variations with varying laser pulse energy for $\lambda = 1.2$ and $\lambda = 1.0$.

It can be seen that there is a slight increase in BP with increasing laser pulse energy. BP increased $\sim$1.3% at $\lambda = 1.2$ and 1% at $\lambda = 1.0$ with increase in laser pulse energy from 9.7 to 24 mJ/pulse. BSFC decreased with increase in laser pulse energy. BSFC reduced from 262 to 258 g/kWh at $\lambda = 1.2$ and from 276 to 273 g/kWh at $\lambda = 1.0$. The reason for enhanced engine performance with increase in laser pulse energies are increased in-cylinder pressures, higher ROHR,

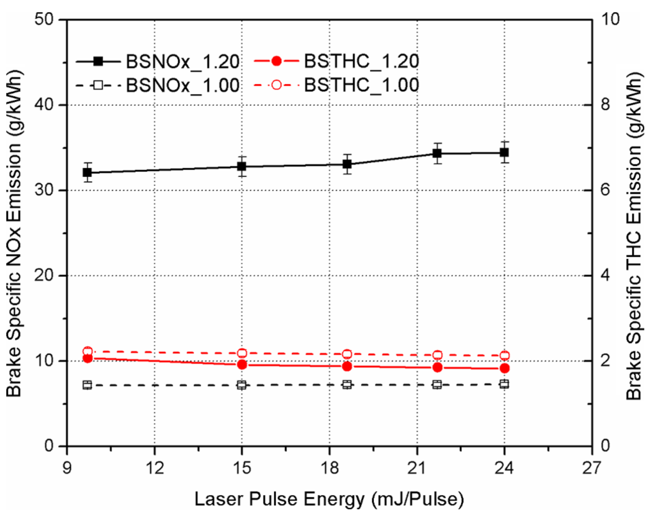

Fig. 11 Brake-specific emissions of NOx and brake-specific emissions of total hydrocarbons with varying laser pulse energy at $\lambda = 1.2$ and $\lambda = 1.0$.

and increased combustion stability as discussed in an earlier section.

Brake-specific emissions of NOx (BSNOx) and total hydrocarbons (BSTHC) are shown in Fig. 11. There is slight increase in BSNOx with increase in laser pulse energy. Increase in BSNOx is due to relatively earlier start of combustion and reduction in ignition delay with increase in laser pulse energy. BSTHC decreased with increase in laser pulse energy. BSTHC reduced by 11 and 4.5% with increase in laser pulse energy at $\lambda = 1.2$ and $\lambda = 1.0$, respectively.

4 Conclusions

The effect of laser pulse energy was investigated in a CVCC as well as in a single-cylinder engine. For higher laser pulse energies, there was a slight change in the maximum chamber pressures; however, it was not significant in CVCC. Time taken to attain the maximum chamber pressure after laser pulse firing (combustion duration) was observed to be lower when combustible mixtures were ignited with higher-energy pulse because of higher laser irradiance at the focal spot. Higher laser irradiance enhanced the flame propagation speed, thereby reducing the combustion duration.

In the engine experiments, maximum cylinder pressure and maximum ROHR increased with increase in laser pulse energy. Ignition delay decreased with increase in laser pulse energy, which increased maximum cylinder pressure and ROHR. COV_{IMEP} decreased with increasing laser pulse energy, which indicated greater combustion stability. Laser irradiance at the focal point played an important role in determining the combustion initiated by laser ignition. It is necessary to provide highest possible laser pulse energy in order to achieve superior combustion stability and engine performance without damaging the piston surface. There was a marginal increase in BP and proportionally marginal reduction in BSFC with increasing laser pulse energy. BSNOx emissions increased with increase in laser pulse energy due to relatively earlier start of combustion as well as reduction in ignition delay. BSTHC emissions, however, decreased with increase in laser pulse energy.

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References

1. R. Maly and M. Vogel, "Initiation and propagation of flame fronts in lean CH_4 – air mixtures by the three modes of the ignition spark," *Sym. (Int.) Combust.* **17**(1), 821–831 (1979).
2. M. Defoort, "Laser ignition for internal combustion engines via fiber optics delivery," PhD Dissertation, Colorado State University (2009).
3. F. L. Jones, "The mechanism of electrode erosion in electrical discharge," *Platinum Met. Rev.* **7**(02), 58–65 (1963).
4. F. A. Soldera et al., "Description of the discharge process in spark plugs and its correlation with the electrode erosion patterns," *IEEE Trans. Veh. Technol.* **53**(04), 1257–1265 (2004).

5. S. Pischinger and J. B. Heywood, "How heat losses to the spark plug electrodes affect flame kernel development in an SI engine," SAE Paper 900021, SAE International (1990).
6. J. D. Dale, M. D. Cheekel, and P. R. Smy, "Application of high energy ignition systems to engines," *Prog. Energy Combust. Sci.* **23**(5–6), 379–398 (1997).
7. R. Maly, "Spark ignition: its physics and effect on the internal combustion process," in *Fuel Economy: In Road Vehicles Powered by Spark Ignition Engines*, John C. Hilliard and S. George, Eds., pp. 91–148, Springer, USA (1984).
8. O. N. A. Hironori, "Development of new iridium alloy for spark plug electrodes," SAE Paper 1999-01-0796, SAE International (1999).
9. L. J. Radziemski and D. Cremers, *Laser-Induced Plasmas and Applications*, Marcel Dekker Inc., New York (1989).
10. T. X. Phuoc, "Laser-induced spark ignition fundamental and applications," *Opt. Laser Eng.* **44**(05), 351–397 (2006).
11. H. Kopecek et al., "Laser ignition of methane–air mixtures at high pressures," *Exp. Therm. Fluid Sci.* **27**(04), 499–503 (2003).
12. D. R. Paul, "Laser versus conventional ignition of flames," *Opt. Eng.* **33**(02), 510–521 (1994).
13. M. Weinrotter et al., "Application of laser ignition to hydrogen–air mixtures at high pressures," *Int. J. Hydrogen Energy* **30**(03), 319–326 (2005).
14. M. Weinrotter et al., "Laser ignition of ultra-lean methane/hydrogen/air mixtures at high temperature and pressure," *Exp. Therm. Fluid Sci.* **29**(05), 569–577 (2005).
15. R. Hickling and W. Smith, "Combustion bomb tests of laser ignition," SAE Paper 740114 (1974).
16. T. X. Phuoc and F. P. White, "Laser-induced spark ignition of CH_4/air mixtures," *Combust. Flame* **119**(03), 203–216 (1999).
17. D. K. Srivastava et al., "Characterization of laser ignition in hydrogen-air mixtures in a combustion bomb," *Int. J. Hydrogen Energy* **34**(05), 2475–2482 (2009).
18. H. Kopecek et al., "Laser ignition of methane-air mixtures at high pressures and diagnostics," *J. Eng. Gas Turbine Power* **127**(01), 213–219 (2005).
19. T. W. Lee, V. Jain, and S. Kozola, "Measurements of minimum ignition energy by using laser spark for hydrocarbon fuels in air: propane, dodecane, and Jet-A fuel," *Combust. Flame* **125**(04), 1320–1328 (2001).
20. M. H. Morsy et al., "Laser-induced two point ignition of premixed with a single shot laser," *Combust. Flame* **124**(04), 724–727 (2001).
21. D. Bradley et al., "Fundamentals of high-energy spark ignition with lasers," *Combust. Flame* **138**(1–2), 55–77 (2004).
22. D. K. Srivastava, K. Dharamshi, and A. K. Agarwal, "Flame kernel characterization of laser ignition of natural gas–air mixture in a constant volume combustion chamber," *Opt. Laser Eng.* **49**(9–10), 1201–1209 (2011).
23. D. K. Srivastava et al., "Laser-assisted homogeneous charge ignition in a constant volume combustion chamber," *Opt. Laser Eng.* **47**(06), 680–685 (2009).
24. J. D. Dale, P. R. Smy, and R. M. Clements, "Laser ignited internal combustion engine—an experimental study," SAE Paper 780329, SAE International (1978).
25. B. Bihari et al., "Development of advanced laser ignition system for stationary natural gas reciprocating engines," in *ASME 2005 Internal Combustion Engine Division Fall Technical Conf.*, ICEF2005-1325, pp. 601–608, ASME (2005).
26. G. Herdin et al., "Laser ignition—a new concept to use and increase the potential of gas engines," in *ASME Internal Combustion Engine Division 2005 Fall Technical Conf.*, ICEF2005-1352, pp. 673–681, ASME (2005).
27. M. H. McMillian et al., "Laser spark ignition: laser development and engine testing," in *ASME 2004 Internal Combustion Engine Division Fall Technical Conf.*, ICEF2004-917, pp. 823–832, ASME (2004).
28. J. D. Mullett et al., "The influence of beam energy, mode and focal length on the control of laser ignition in an internal combustion engine," *J. Phys. D Appl. Phys.* **40**(15), 4730–4739 (2007).
29. J. Graf et al., "Laser ignition, optics and contamination of optics in an I.C. engine," in *ASME 2004 Internal Combustion Engine Division Fall Technical Conf.*, ICEF2004-833, pp. 11–17, ASME (2004).
30. D. K. Srivastava and A. K. Agarwal, "Laser ignition of single cylinder engine and effects of ignition location," SAE Paper No. 2013-01-1631 (2013).
31. T. Alger et al., "Laser ignition in a pre-mixed engine: the effect of focal volume and energy density on stability and the lean operating limit," SAE Paper 2005-01-3752, SAE International (2005).
32. W. M. Steen, *Laser Material Processing*, 3rd ed., Springer, London (2003).
33. J. B. Heywood, *Internal Combustion Engines Fundamentals*, McGraw-Hill Book Company, New York (1988).
34. Y. L. Chen, J. W. L. Lewis, and C. Parigger, "Spatial and temporal profiles of pulsed laser-induced air plasma emissions," *J. Quant. Spectrosc. Radiat. Transf.* **67**(02), 91–103 (2000).

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