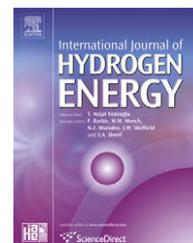


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Technical Communication

Characterisation of laser ignition in hydrogen–air mixtures in a combustion bomb

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ABSTRACT

Laser-induced spark ignition of lean hydrogen–air mixtures was experimentally investigated using nanosecond pulses generated by Q-switched Nd:YAG laser (wavelength 1064 nm) at initial pressure of 3 MPa and temperature 323 K in a constant volume combustion chamber. Laser ignition has several advantages over conventional ignition systems especially in internal combustion engines, hence it is necessary to characterise the combustion phenomena from start of plasma formation to end of combustion. In the present experimental investigation, the formation of laser plasma by spontaneous emission technique and subsequently developing flame kernel was measured. Initially, the plasma propagates towards the incoming laser. This backward moving plasma (towards the focusing lens) grows much faster than the forward moving plasma (along the direction of laser). A piezoelectric pressure transducer was used to measure the pressure rise in the combustion chamber. Hydrogen–air mixtures were also ignited using a spark plug under identical experimental conditions and results are compared with the laser ignition ones.

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1. Introduction

Advancing the state of the art of ignition systems for lean burn, stationary, natural gas fuelled engines is crucial to meet increased performance requirements. Severely reduced spark plug performance and durability is an unfortunate consequence as engines are simultaneously being pushed to higher power densities and leaner stoichiometry in order to improve efficiency and lower emissions. To compensate power density losses due to leaner operation, high pressure of initial charge

is used to increase in-cylinder pressure at the time of combustion. However, an important parameter is the ignition under extreme conditions, lean combustible mixture and high initial pressure, requiring high voltage when using conventional spark plug technology. Providing the necessary spark energy to operate these engines significantly reduces the lifetime of spark plugs. An alternative solution to standard spark plug is the use of pulsed laser, focused to create plasma, representing the laser ignition. Laser ignition also has the advantage of giving lower emissions particularly lower NO_x

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emissions due to absence of quenching effects, which are present in the case of ignition by a spark plug. Laser ignition allows combustion of leaner fuel-air mixtures therefore lower NO_x emission formation takes place. This is a huge advantage for engines and is one of the main motivations to develop laser ignition for large-size gas engines. This investigation is a step forward in this direction.

Laser ignition can be divided into two main parts. The first one is the spark creation due to the local deposition of energy. This can be achieved in any gas. Breakdown is associated with plasma formation and shock wave generation. The second part is the ignition itself based on a positive balance between the deposited energy and the losses. In this case, a flame kernel can develop.

Interest in laser ignition has increased in recent years because of its many potential benefits over conventional ignition system. The main advantages of laser ignition are:

- Arbitrary positioning of the ignition plasma in the combustion chamber
- Absence of quenching effects by the spark plug electrodes, which allows ignition of leaner mixtures and consequently lower NO_x formation
- Because of absence of erosion effects as with the spark plug, the lifetime of a laser-ignition system is significantly longer
- Precise ignition timing
- Simpler regulation of the ignition energy deposited in the ignition plasma
- Easy possibility of multipoint ignition to speed up the low combustion speed of lean mixtures [1–3]

The possibility of choosing the location of the focal point in the cylinder is a significant advantage for the combustion process. It is possible to position the plasma exactly in the middle of the cylinder. High load/ignition pressure of the gas engine for optimum efficiency demands increasing spark plug voltage, leading to enhanced erosion of the electrodes. Therefore, it is a main aim to increase the lifetime of an ignition system and minimise the service efforts. A diode-pumped laser ignition system has potential lifetime up to 10,000 h compared to spark plug lifetimes on the order of 2000–4000 h (source: G.E. Jenbacher, Austria). The efficiency of a diode-pumped laser is approximately 10%. Furthermore, with the possibility of multipoint ignition, the combustion can be started with two or more plasmas at different points but at the same time in the cylinder which further shortens the total combustion duration significantly.

In laser ignition, when a powerful laser beam (irradiance on the order of 10^{12} W/cm^2) interacts with a combustible mixture, a plasma of high temperature (on the order 10^6 K) and high pressure (on the order of 100 MPa) is created at the end of the laser pulse [4,5].

The predominant plasma generating effect is the electron cascade process. In this process, initial electrons absorb photons out of the laser beam via the inverse *bremsstrahlung*. If the electrons gain sufficient energy, they can ionise other gas molecules on impact, leading to an electron cascade and breakdown of the gas in the focal region. It is important to note that this process requires initial seed electrons. These electrons are produced from impurities in the gas mixture (e.g.

dust, aerosol or soot particles) [6], which absorb the laser radiation, leading to increased local temperature and free electrons, which start the avalanche process. Significant wavelength dependence is expected for this initiation effect, according to Drude model. It is very unlikely that the first free electrons are produced by multiphoton ionisation because the intensity in the focus (10^{12} W/cm^2) is too low to ionise gas molecules via this process, which requires higher irradiance ($\geq 10^{14} \text{ W/cm}^2$).

Fig. 1 shows an overview of the processes involved in laser-induced ignition covering several orders of magnitude in time from the nanosecond domain of the laser pulse itself to the duration of the entire combustion lasting several hundreds of milliseconds in the constant volume combustion chamber. The laser energy is deposited in a few nanoseconds, which leads to a shock wave generation. In the first few milliseconds, an ignition delay can be observed which has duration between 5 and 100 ms depending on the mixture ratio. Combustion can last between 100 and 2000 ms, again depending on the gas mixture ratio, initial pressure, laser pulse energy, plasma size, position of the plasma in the combustion chamber and initial temperature.

Several potential benefits and applications of laser ignition were reviewed by Ronney [8]. Most laser ignition experiments have been carried out with methane-air mixtures [1,2,9–18] and few with hydrogen-air mixtures [3,19–22]. The minimum pulse energy for ignition (MPE) decreases drastically with the initial pressure [10,13,14,23–27]. Further on, MPE increases towards the lean and rich side of the stoichiometry [13,14,16,24–26]. There is no significant wavelength dependence of the MPE in practical gas mixtures, supporting the hypothesis of small impurity particles proving the seeds for laser plasma generation involving a thermionic process, which is non-resonant [11,14]. Moreover with higher laser energies than MPE, ignition delay can be shortened [3,14] and, as explained above, laser ignition has shorter ignition delay and reduced total combustion duration compared to conventional spark ignition [10–12]. If flames are initiated simultaneously at multiple locations using laser ignition, more efficient combustion can be achieved and total combustion

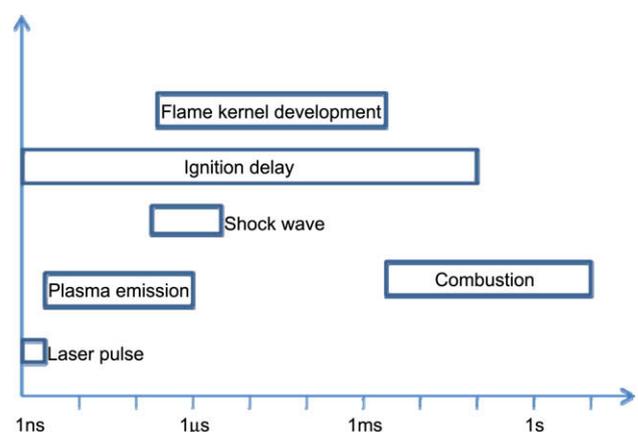


Fig. 1 – Range of timescales for various processes involved in laser-induced ignition: the lengths of the box indicate the durations of the indicated processes [7].

duration can be reduced significantly compared to single-point ignition [8]. Ma et al. [12] found that the flame velocity in laser ignited gas mixture is faster than that in conventionally ignited mixtures. This is a very important observation of ignition of lean mixture to speed up the combustion duration for practical application.

Spiglanin et al. [19] studied laser ignition of hydrogen–air mixtures. By observing shape and structure of the flame kernel growth, they suggested that early flame kernel growth is dominated by the gas motion, which is induced by the short duration plasma spark.

The difficulties associated with a practical laser ignition system include very high cost of a laser, optical hardware and a transport mechanism (including perfect alignment) of laser beam in to the combustion chamber.

2. Experimental set-up

In the present research, two different experimental set-ups were used. The first set-up is used for measurement of plasma in laminar air flow using spontaneous emission technique. The second is utilised for flame kernel measurement in lean hydrogen–air mixture using the Schlieren technique.

A Q-switched Nd:YAG laser was used, delivering pulse energy up to 250 mJ and a pulse duration of 5 ns at full width half maximum (FWHM) at the fundamental wavelength at 1064 nm. The beam diameter was 5.7 mm ($1/e^2$) with a beam quality of $M^2 < 2$. The laser energy could be attenuated continuously by using an external wave plate/polariser set-up without affecting any laser parameters such as pulse duration or spatial beam profile. A part of the laser beam ($\sim 4\%$) was used to measure the energy of each pulse using a pyroelectric detector (SpectroLasPEM21) and an energy measuring unit (LEM2020).

The laser plasma in laminar air flow at atmospheric condition (laser pulse energy of 20 mJ) was measured. A best-form lens with a focusing length $f = 50$ mm was used for focusing the laser beam. Fig. 2 shows the experimental setup for measurement of laser plasma observing the near ultraviolet spectrum of the emitted radiation ($\lambda = 330$ nm) with 3 ns temporal resolution. The images are captured using a lens of focal length 100 mm and the ICCD camera that views the

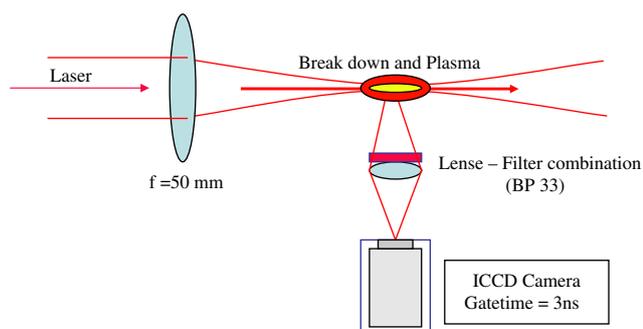


Fig. 2 – Experimental set-up for measurement of laser plasma with the spontaneous emission technique.

plasma orthogonally to laser propagation. The ICCD camera was only able to take one picture per plasma formation.

Schlieren photography was conducted in the plane of the focal spot of the laser ignition. Perpendicular to the ignition laser beam, collimated light from a flash lamp (1 ms pulse duration) was directed through the combustion chamber. Since refraction index in gases is strongly dependent on the density, areas with gradients of temperatures or pressures have a considerable effect on the propagation of light. The refraction angle is proportional to the first derivative of these parameters. The experimental set-up for the Schlieren experiments is shown in Fig. 3.

The spherical mirror used in this experimental setup has two functions: (1) it focuses the unscattered part of the incoming parallel light to the focal point and (2) it creates a real and inverted image of the flame kernel on the CCD chip of the camera. A high temporal resolution may be achieved either by using a fast light source or a fast camera. Here, a fast gateable intensified camera (DiCAM Pro, PCO Imaging, min. exposure time 3 ns) is used. A major advantage in Schlieren photography is its simple experimental set-up. The major disadvantage of this technique is that information from a volume (3-D) is shown on a plane (2-D).

The combustion process was characterised by its pressure history measured using a piezoelectric pressure transducer (Kistler 7061B; response time 8.8 μ s). The signals from the sensor had to be amplified using a charge amplifier and were recorded in a digital storage oscilloscope. Both the pressure signals and the laser pulses were recorded in a computer.

For all experiments, compressed air (moisture free) and hydrogen (with a purity of $< 99.9\%$) were used in order to yield data relevant for practical applications. For achieving the intended ratio of the gaseous mixture components according to the partial pressure law (Dalton law), it was necessary to measure the partial pressure of hydrogen and air using a high-resolution (least count = 100 Pa) pressure gauge. In order to ensure safety during the hydrogen filling process, the chamber was evacuated to about 2.5 kPa first and only then hydrogen was filled up to the calculated pressure for different mixtures. After this operation was complete, air was filled into the combustion chamber.

To ensure homogeneity of the mixture, hydrogen was introduced first in to the chamber since this is the species having lower partial pressure. Homogeneity could be easily achieved by the turbulence generated by incoming air. Also because of the high diffusion coefficient of hydrogen ($D = 61$ mm²/s, at atmospheric pressure and 298 K) homogeneity was reasonably assured. A 1-min pause before each ignition attempt guaranteed a homogeneous mixture. The internal diameter and length of the combustion chamber were 70 and 220 mm, respectively. The maximum filling pressure was 3 MPa and the chamber was heated up to an initial temperature 323 K for each combustion attempt.

3. Results and discussion

In many ways, the laser-induced plasma is similar to direct current arcs that are created in similar gases under similar

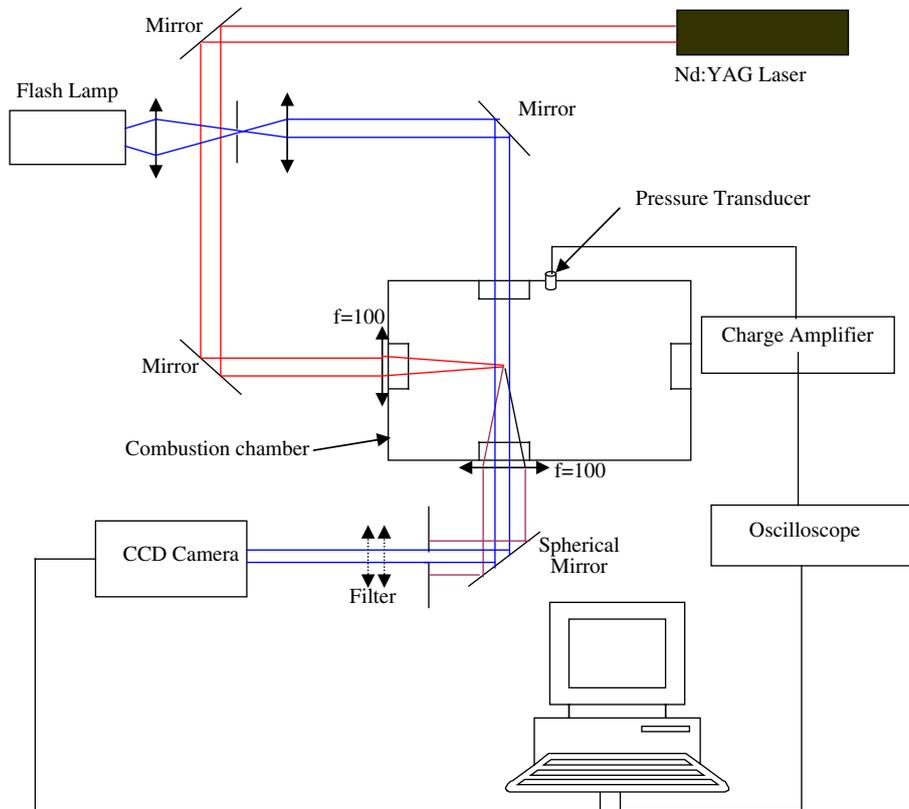


Fig. 3 – Experimental set-up for Schlieren photography.

pressures. However, the laser plasma will generally be more compact and has a higher maximum temperature than other continuous arcs [28,29]. Moreover, the plasma can be sustained in a steady state well away from containing boundaries. The fundamental difference is in the way and time in which energy is absorbed, and which is responsible for this unique characteristic of laser plasma.

The size of the laser plasma depends on several factors including the beam geometry, laser power and absorption coefficient. The change in intensity of the laser beam as it propagates within the plasma is given by Beer's law:

$$\frac{dI}{ds} = -\alpha I$$

Here I is the intensity of the laser beam and s is the distance along the direction of beam propagation. The absorption length $1/\alpha$ is a dominant length scale for the laser plasma since it determines the distance over which the power is absorbed from the beam. On one hand, the length of the plasma along the beam axis is influenced by the absorption length whereas, on the other hand, it is the laser beam diameter that mainly affects the plasma diameter. The plasma expands to fill the beam cone where it is able to absorb power, and then rapidly decreases in temperature outside the beam through thermal conduction and radiation.

Initially, the plasma behaviour at atmospheric condition using 3-ns-gated fast photography was investigated. Fast photography provides information on spatial and temporal behaviour of plasma after the onset of the spark and it is

considered to be one of the best diagnostic tools for studying plasma expansion dynamics [29]. Fig. 4 shows various stages of plasma growth in air with respect to time measured with the experimental setup depicted in Fig. 2 with the spontaneous emission technique. The laser beam entered from the right side. In order to study the temporal evolution of the ignition process, multiple images had to be recorded from multiple ignition events. All images in Fig. 4 have a physical height and width of 0.41 mm and 0.83 mm respectively. The fluctuation of the Nd:YAG laser pulse energy output was found to be less than 1% of the pulse power. The recorded plasma images in the experiment were highly repetitive.

The first image of the plasma appeared 6 ns after the starting of laser pulse (pulse energy 20 mJ). The images were also measured for higher pulse energies and it was observed that with higher pulse energy, the first images of plasma appeared earlier. The initial plasma propagated towards the incoming laser beam to seek the position of stability where loss of energy due to conduction and radiation is equal to the laser energy absorbed. The backward moving plasma (towards the focusing lens) grows much faster than the forward moving plasma (along the direction of laser). There is no physical background for any delay. Only the density determines its absorbance. After a certain delay, the plasma becomes strongly absorbing for the laser beam and it expands out of the focal volume in combination. After the pulse has ended, the plasma will continue to expand, though very slowly [28–30] and at 30 ns it had the maximum emission intensity. The

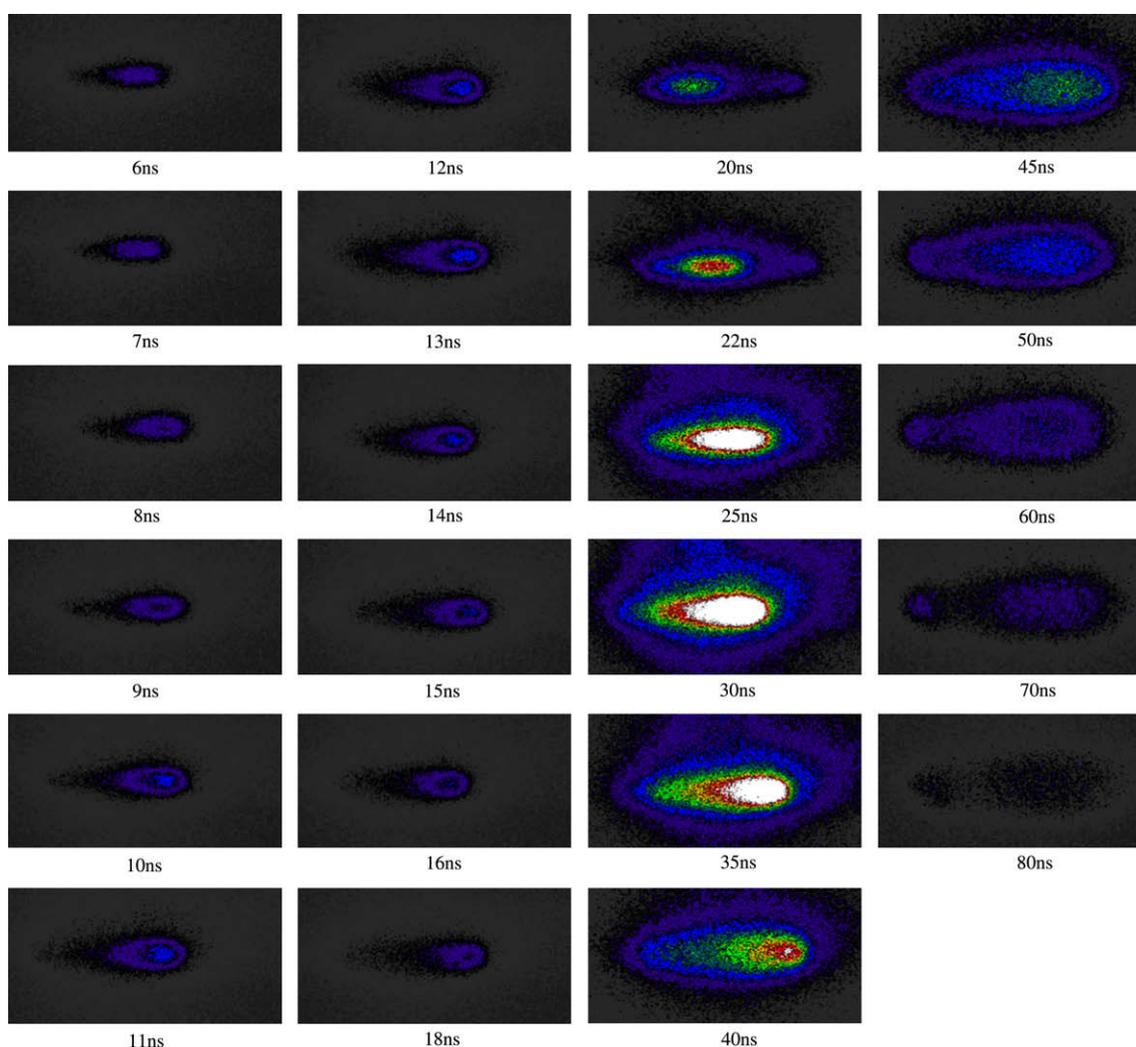


Fig. 4 – Various stages of plasma growth in air in form of the plasma emission (Wavelength = 330 nm).

maximum diameter and length of the laser plasma at 30 ns was 0.01 mm and 0.27 mm, respectively, as is depicted in Fig. 5. The plasma emission lasts about 80 ns after the laser pulse.

In these experiments, only the backward moving component of the spark was observed. The reason behind the propagation of plasma is that the layer of gas outside the plasma, though is transparent for the laser beam, gets heated by the plasma. This gas close to the plasma will then get ionised on heating to such an extent that it will strongly absorb the laser beam. On absorption of laser pulse energy, this layer will be further heated extremely rapidly and the temperature will increase very fast. By this time, another gas layer near the plasma will become strongly absorbing to laser, hence the boundary of the plasma will start moving towards the focusing lens. The time scale of this event is similar to that of the laser pulse itself. After the pulse has ended, the plasma will continue to expand, though very slowly (Fig. 4).

Glumac and Elliott [30] suggested that at atmospheric pressure, the plasma breakdown initiates at a location slightly before the focal point of the lens, with the region of highest emission propagating toward the incoming laser beam. As the pressure decreases below 0.05 MPa, the laser spark originates

from a central point and propagates both towards and away from the focal point, resulting in a larger total area of the spark and a bimodal structure. This nature of propagation of plasma is also confirmed by Chen et al. [28]. Conclusively, it can be

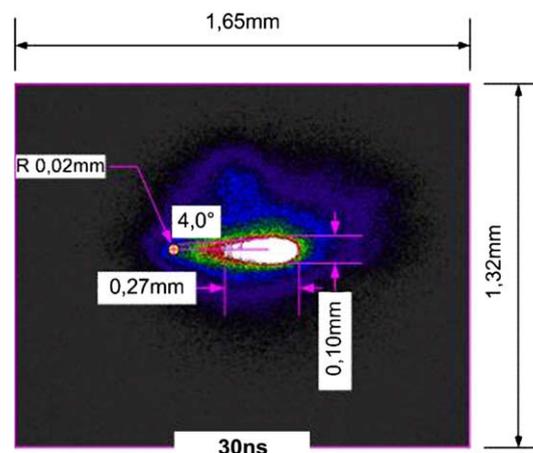


Fig. 5 – Emission of the laser plasma ($\lambda = 330$ nm) 30 ns after the laser pulse of 20 mJ pulse energy, laser beam entering from right to left.

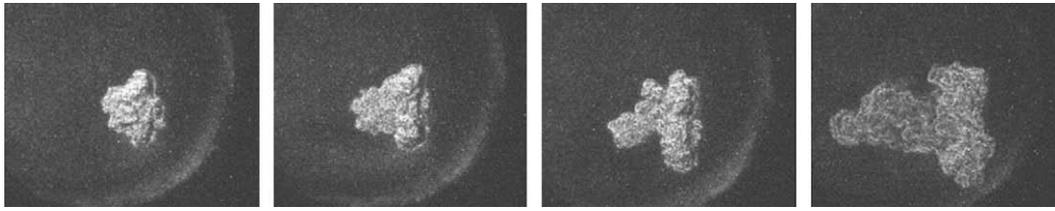


Fig. 6 – Schlieren photograph of flame kernel developments by laser ignition in hydrogen–air mixture ($\lambda = 6.0$) after 100 μs , 200 μs , 300 μs , 1000 μs (from left to right); laser entering from left to right.

said that the direction of plasma movement depends on the pressure to a large extent.

Schlieren photography was used to obtain visual information on the shock wave formation and flame kernel development, as displayed in Fig. 3. Lamoureux et al. [22,31,32] measured the shape of flame kernel in hydrogen–air mixture ignited through a spark plug. At 0.1 MPa, the shape of flame kernel was found as a disk whose diameter increases with time. Phouc [23] investigated the shape of the laser-induced spark in air. At low pressure (0.02 MPa), a nearly perfect cylindrical shape of the size of the focal spot was observed. At 0.4 MPa, the shape was reported to be cone-like with the larger size facing towards the igniting laser.

Fig. 6 shows typical Schlieren images of laser ignited hydrogen–air mixtures at 2.5 MPa and a combustion bomb temperature of 373 K. The images are 11.6 mm long and 9.15 mm high. The air/fuel equivalence (λ) ratio was 6.0. Schlieren images were taken at 100, 200, 300 and 1000 μs (from left to right) after ignition. The laser beam entered from the left side. One can see the typical structures of a laser-induced flame: the torus and the front lobe. The toroidal shape of plasma kernel appears to be a universal phenomenon of both electric spark and laser spark. The development of the electric spark kernel is symmetric along its axis while

the laser spark is always asymmetric due to the optical focusing geometry. One can also see the formation of shock wave in the mixture. The shock wave has two major implications on laser ignition: First, it transports energy away from the ignition spot, and second, it causes a significant temperature rise in the combustion chamber. The shock wave initially has an ellipsoidal shape caused by the asymmetric energy deposition of the laser. At a later stage, as it propagates outward, the shock wave front is found to approach a spherical geometry [24].

Fig. 7 shows a pressure history diagram inside the combustion chamber for different mixtures ($\lambda = 2.5\text{--}3.5$) at initial pressure and temperature of 3 MPa and 323 K, respectively, ignited by laser (laser pulse energy = 20 mJ) and spark plug (G.E. Jenbacher P7 with a spark gap of 0.35 mm and coil energy of 180 mJ) keeping same initial experimental condition. It can be seen that peak pressures in both cases (i.e. laser ignition and spark plug ignition) are comparable. The time of pressure rise in the case of laser ignition is shorter. This may be because of absence of flame quenching in the case of laser ignition. However, another possible reason may be the energy that was actually transferred into the gas phase by these different ignition processes. Different energy contents might create different initial spark volumes, from which flame propagation starts. Also, a clear

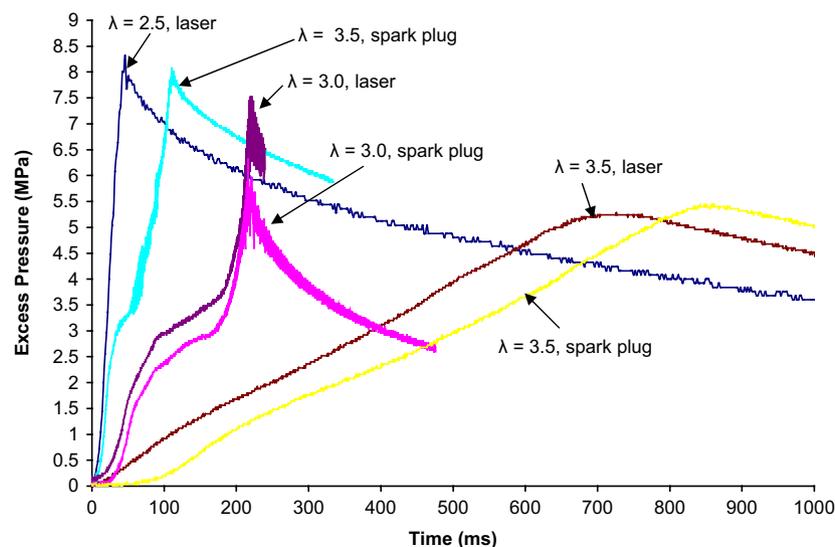


Fig. 7 – Pressure history of hydrogen–air mixture in the combustion chamber after laser ignition and spark plug ignition ($\lambda = 2.5\text{--}3.5$, initial chamber pressure = 3 MPa, initial chamber temperature = 323 K).

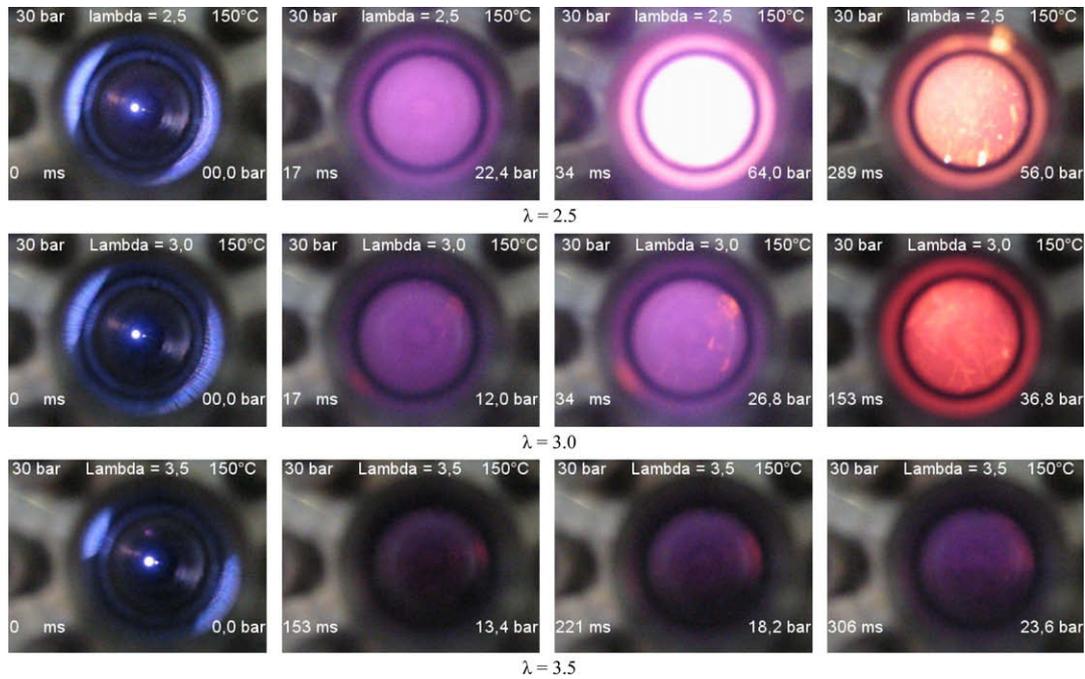


Fig. 8 – Video images of laser ignited hydrogen-air mixtures.

trend towards longer combustion times with leaner mixtures can also be observed, which is explained in the faster flame velocity of richer gas mixtures. As expected, the peak pressure decreases with leaner mixtures.

High-speed video pictures were also captured for laser and spark plug ignited hydrogen-air mixtures, as shown in Figs. 8 and 9. One can see that the laser-induced plasma is always at

a fixed position but spark plug ignition plasma is moving around the circumference of spark electrodes. This is one of the advantages of laser ignition: that the plasma can be placed precisely anywhere inside the combustion chamber by choosing a suitable optical system. As laser plasma is created without electrodes, there is no quenching effect, which helps in igniting leaner hydrogen-air mixtures.

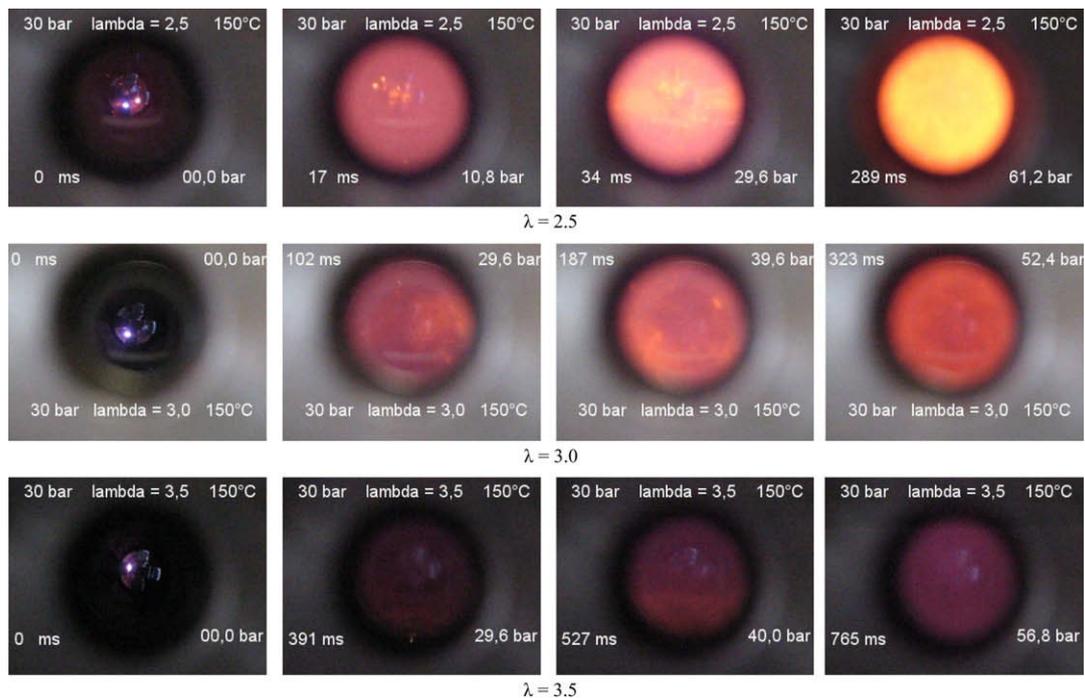


Fig. 9 – Video images of spark plug ignited hydrogen-air mixtures.

4. Conclusions

Laser ignition of lean hydrogen–air mixtures was successfully carried out in a constant volume combustion chamber at a chamber temperature of 323 K and an initial pressure of 3 MPa. Laser plasma evolution in air under atmospheric condition was characterised in detail by measuring the plasma emission ($\lambda = 330$ nm). It was found that initially the plasma propagates towards the incoming laser beam. After the pulse is terminated, the plasma is still very hot and expands, thereby generating a shock wave. Under the experimental conditions discussed above, plasma had the maximum emission peak 30 ns after the laser was fired and laser plasma UV-emission persisted for about 80 ns. Schlieren images of the flame kernel were taken at 100, 200, 300 and 1000 μ s after ignition. The flame kernel was asymmetric along the focal axis because of optical focusing geometry.

The rate of pressure rise inside the combustion chamber was higher when the mixture was ignited by laser plasma compared to spark plug ignition. This may be because of the absence of a plasma quenching effect.

REFERENCES

- [1] Phouc TX. Single-point versus multi-point laser ignition: Experimental measurements of combustion time and pressures. *Combustion & Flame* 2000;122:508–10.
- [2] Morsy MH, Ko YS, Cho P. Laser induced two point ignition of premixture with a single-shot laser. *Combustion & Flame* 2001;125:724–7.
- [3] Morsy MH, Chung SH. Laser-induced multi-point ignition with a single-shot laser using two conical cavities for hydrogen/air mixture. *Experimental Thermal & Fluid Science* 2003;27:491–7.
- [4] Phouc TX, White FP. Laser-induced spark ignition of CH₄/air mixtures. *Combustion & Flame* 1999;119:203–16.
- [5] Radziemski LJ, Cremers DA. *Laser-induced plasma and applications*. New York, Basel: Marcel Dekker; 1889.
- [6] Yablouovich E. Self phase modulation and short pulse generation from laser breakdown plasmas. *Physical review A* 1979;10:1888–95.
- [7] Weinrotter M, Ast G, Kopecek H, Wintner E. An extensive comparison of laser-induced plasma ignition and conventional spark plug ignition of lean methane–air mixtures under engine like conditions, SAE Paper No. 2005-01-0248.
- [8] Ronney PD. Laser versus conventional ignition of flames. *Optics Engineering* 1994;33(2):501–21.
- [9] Kopecek H, Charareh S, Lackner M, Forsich C, Winter F, Klausner J, et al. Laser ignition of methane-air mixtures at high pressures and diagnostics. *Proceedings of ICE Combustion Division, Salzburg, Austria, 2003*.
- [10] Kopecek H, Charareh S, Lackner M, Forsich C, Winter F, Klausner J, et al. Laser ignition of methane-air mixtures at high pressures and diagnostics. *Second Mediterranean Combustion Symposium. The Combustion Institute, Sharm El-Sheikh, Egypt 2002:881–7*.
- [11] Ma JX, Alexander DR, Poulain DE. Laser spark ignition and combustion characteristics of methane-air mixtures. *Combustion & Flame* 1998;112:492–506.
- [12] Ma JX, Ryan TW III, Buckingham JP. Nd:YAG Laser ignition of natural gas. ASME Spring Technical Conference, Paper No. 1998:ICE-114.
- [13] Phouc TX, White FP. Laser-induced spark ignition of CH₄/air mixtures. *Combustion & Flame* 1999;33(2):510–21.
- [14] Kopecek H, Maier H, Reider G, Winter F, Wintner E. Laser ignition of methane-air mixtures at high pressures. *Experimental Thermal & Fluid Science* 2003;27:499–503.
- [15] Morsy MH, Ko YS, Chung SH. Laser-induced ignition using a conical cavity in CH₄/air mixtures. *Combustion & Flame* 1999;119:473–82.
- [16] Beduneau JI, Kim B, Zimmer L, Ikeda Y. Measurements of minimum ignition energy in premixed laminar methane/air flow by using laser induced spark. *Combustion & Flame* 2003; 132:653–65.
- [17] Morsy MH, Chung SH. Numerical simulation of front lobe formation in laser-induced spark ignition of CH₄/air mixtures. *Proceedings of Combustion Institute, Sapporo, Japan, 2002;29:1613–1619*.
- [18] Chen YL, Lewis JWL. Visualisation of laser-induced breakdown and ignition. *Optic Express* 2001;9(7):360–72.
- [19] Spiglanin TA, McIlroy A, Fournier EW, Cohen RB, Syage JA. Time resolved imaging of flame kernels: laser spark ignition of H₂/O₂/Ar mixtures. *Combustion & Flame* 1995;102:310–28.
- [20] Weinrotter M, Kopecek H, Wintner E, Lackner M, Winter F. Application of laser ignition to hydrogen–air mixtures at high pressures. *International Journal of Hydrogen Energy* 2005;30: 319–26.
- [21] Qin X, Kobayashi H, Niioka T. Laminar burning velocity of hydrogen–air premixed flames at elevated pressure. *Experimental Thermal and Fluid Science* 2000;21:58–63.
- [22] Lamoureux N, Djebaili-Chaumeix N, Paillard CE. Laminar flame velocity determination for H₂–air–He–CO₂ mixtures using the spherical bomb method. *Experimental Thermal and Fluid Science* 2003;27:385–93.
- [23] Phuoc TX. Laser spark ignition: experimental determination of laser-induced breakdown thresholds of combustion gases. *Optics Communication* 2000;175:419–23.
- [24] Lewis B, Von Elbe G. *Combustion, flames and explosions of gases*. 3rd ed. New York: Academic Press, Hartcourt Brace Jovanovich Publishers; 1987.
- [25] Lee TW, Jain V, Kozola S. Measurements of minimum ignition energy by using laser sparks for hydrocarbon fuels in air: propane, dodecane, and jet-A fuel. *Combustion & Flame* 2001;125:1320–8.
- [26] Ronney PD, Lim E, McIlroy A, Syage JA. Laser ignition studies. 2001. http://cpl.usc.edu/Laser_Ignition.
- [27] Ronney PD. Effect of gravity on laminar premixed gas combustion II: ignition and extinction phenomena. *Combustion & Flame* 1985;62:121–33.
- [28] Chen YL, Lewis JWL, Parigger C. Spatial and temporal profiles of pulsed laser-induced air plasma emissions. *Journal of Quantum Spectroscopy and Radiative Transfer* 2006;76: 91–103.
- [29] Bindhu CV, Harilal SS, Tillack MS, Najmabadi F, Gaeris AC. Laser propagation and energy absorption by an argon spark. *Journal of Applied Physics* 2003;94(12):7402–7.
- [30] Glumac N, Elliott G. The effect of ambient pressure on laser-induced plasmas in air. *Optics and Lasers in Engineering* 2007;45:27–35.
- [31] Tang C, He J, Huang Z, Jin C, Wang J, Wang X, et al. Measurement of laminar burning velocities and Markstein lengths of propane–hydrogen–air mixtures at elevated pressures and temperatures. *International Journal of Hydrogen Energy* 2008;33(23):7274–85.
- [32] France DH. Combustion characteristics of hydrogen. *International Journal of Hydrogen Energy* 1980;5:369–74.