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Combustion characteristics and flame-kernel development of a laser ignited hydrogen–air mixture in a constant volume combustion chamber

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ABSTRACT

Laser ignition of hydrogen–air mixture was carried out in a constant volume combustion chamber (CVCC) at 10 bar initial chamber filling pressure and 373 K chamber temperature. A Q-switched Nd:YAG laser at 1064 nm with a pulse duration of 6–9 ns was used for plasma generation and ignition of combustible hydrogen–air mixture. Pressure–time history of different hydrogen–air mixtures was measured in the CVCC and flammability limits of hydrogen–air mixture were measured. Flame kernel development was investigated for different air–fuel mixtures using Shawdowgraphy and flame propagation distances were calculated. Minimum ignition energy was measured for hydrogen–air mixtures of different air–fuel ratios and effect laser pulse energy on pressure–time history in the CVCC was experimentally measured. Upon increasing the laser pulse energy, time taken to attain peak cylinder pressure reduced which resulted in faster combustion in hydrogen–air mixtures however the peak cylinder pressure remained similar.

1. Introduction

Engine manufactures are currently seeking to develop internal combustion (IC) engines, which are more fuel efficient, refined and produce lower emissions, and are capable of using alternate fuels such as biodiesel, alcohols, CNG, hydrogen etc. In recent years, hydrogen fuelled IC engines have become increasingly attractive, first because of their extremely low pollution potential, and second because of the potential use of hydrogen as synthetic fuel. The only harmful pollutant emitted by combustion of hydrogen–air mixture is NO_x. Hydrogen is perhaps an ideal fuel in view of its ability to be generated from a host of primary renewable energy sources. Hydrogen is a unique and versatile fuel, which has the potential to provide solution for fossil fuel depletion and global environmental issues simultaneously. A close look at the fuel properties of hydrogen brings in very important aspects w.r.t. its feasibility for engine operation. Interestingly, most of the properties of hydrogen if exploited appropriately, would prove to be points of advantage and will be desirable. Hydrogen has a wide flammability range in comparison to all other known fuels, therefore it is very easy to operate hydrogen engine with extremely lean mixtures. Hence, fuel economy will be greater and the combustion reactions would also be complete to a greater degree. Additionally, maximum

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combustion temperatures inside the combustion chamber would also be lower for lean air–fuel mixtures compared to stoichiometric mixture, which would reduce the noxious pollutants [1,2]. In addition, stoichiometric hydrogen–air mixture has an extremely low ignition energy requirement, higher flame speed and higher diffusivity compared to stoichiometric gasoline–air mixture [3]. However, extremely low ignition energy makes the system susceptible to surface ignition. Surface ignition is a highly undesirable combustion phenomenon caused by uncontrolled ignition of fuel–air mixture and can be initiated by an overheated valve or a spark plug, glowing combustion chamber deposits, or any other hot spot in the combustion chamber [4]. The surface ignition may occur even before the spark plug initiates normal ignition or sometimes after the normal spark. Because of surface ignition, the spark discharge no longer has complete control on the combustion process, which has severe implications upon engine operation and structural safety.

Since, hot tip of a spark plug is the most suspected source of surface ignition in a hydrogen fuelled engine, an electrode-free ignition system should be considered for developing a commercial hydrogen fuelled IC engine. An alternative solution to standard spark plug is the use of a pulsed laser, which may be focused to generate intense plasma, representing laser ignition. Stringent emission norms and demand for high thermal efficiency can also be met by igniting relatively leaner fuel–air mixtures. However, such mixtures lead to lower power density therefore lower power output also. Loss of power output can be compensated by increasing intake charge pressure by employing turbocharging, which also leads to higher in-cylinder pressures. Higher in-cylinder pressure at the time of ignition however requires higher voltage to ignite the combustible mixture in a conventional spark ignition system. Such high voltages unfortunately lead to rapid spark electrode erosion therefore lowers the life span of the spark plugs. However, higher in-cylinder pressures are in fact a favorable condition for laser ignition because minimum ignition energy required for initiating combustion actually decreases with increasing cylinder pressure [5]. In view of these special features, laser ignition has significant potential to ignite relatively leaner mixture without loss of power output in addition to reducing emissions.

Laser ignition has been a subject of research since 1970's. Use of laser pulses for ignition of combustible air–fuel mixture has several advantages over conventional spark ignition such as possibility of free positioning of plasma, absence of electrode erosion effects, feasibility to ignite leaner mixtures, precise ignition timings etc. Furthermore, with the possibility of multipoint ignition, combustion can be initiated by two or more plasma sparks at multiple locations at the same time in the combustion chamber, which can possibly shorten the combustion duration significantly because of reduction in maximum distance of flame travel [6,7]. Major reasons to prefer laser ignition over conventional spark ignition is the feasibility of a having lower lean limit for ignition together with higher ignition pressures, leading to higher efficiency and significantly lower NO_x emissions [8].

Studies in the past reported successful and reliable laser ignition of CNG-air mixtures [9]. However only few such studies have been done for hydrogen. Ma et al. [10] found that the flame velocity in laser ignited gas mixtures is faster than in conventionally ignited mixtures. Using laser ignition, pressure rise in the combustion chamber was seen to be significantly higher compared to conventional spark ignition under identical conditions [11]. Weinrotter et al. [12] and Srivastava et al. [5] also showed that peak cylinder pressure decreased as the relative air–fuel ratio (λ) of the mixture increased i.e. mixture became leaner. Morsy et al. [13] showed that using multi-point laser ignition leads to faster combustion of fuel–air mixture with no significant change in the peak pressure. Changjian et al. [14] showed that flame velocity increased upon increasing initial pressure as well as increasing laser pulse energy.

In light of these studies, the present experimental study was focused on investigating different aspects of laser ignited hydrogen–air mixture in a constant volume combustion chamber (CVCC). Different stages of flame kernel development were captured and analyzed to find flame speed and flame kernel evolution with time. Pressure–time history and net heat release were also measured for hydrogen–air mixtures of varying relative air–fuel ratios.

2. Experimental setup

The experimental setup included laser for plasma ignition and a CVCC. A high speed camera and a piezoelectric pressure transducer were used for visualizing flame kernel evolution and measuring the in-cylinder pressure–time history respectively. Experiments were performed on different hydrogen–air mixtures prepared using Zero grade hydrogen and moisture free compressed air, which were mixed to form homogeneous combustible mixture. For achieving the intended fuel–air ratio, Dalton's law of partial pressures was used. The partial pressures of hydrogen and air were measured using two high resolution digital manometers (Thommen; HM35). After each experiment, the CVCC was evacuated to 2.5 mbar using a vacuum pump. Then hydrogen was filled to the calculated partial pressure. Air was then introduced into the CVCC to take it upto the final pressure. Hydrogen has very high diffusion coefficient (0.61 cm^2/s). Hydrogen was introduced in the geometrical center of CVCC. Therefore the maximum diffusion area was 11 cm × 7.2 cm. The diffusion time was calculated by the equation $t = X^2/2d$, where X is the longest dimension (11 cm) and d is the diffusion coefficient (0.61 cm^2/s). Therefore the time required for diffusion of hydrogen air-mixture is 99.18 s. Mixture was therefore allowed to diffuse for homogenization for 2 min before the ignition experiment. Initial temperature of CVCC was maintained at 373 K using finger heater of adequate capacity and a PID controller, in order to simulate the engine combustion chamber conditions prevailing at the time of ignition. The CVCC was installed with finger heaters (6 Nos; 750 W each) to heat the chamber contents. The temperature of CVCC was measured using a thermocouple located in the central section. Heating was controlled and the temperatures were maintained using the PID controller. Fig. 1 illustrates the schematic of the experimental setup. Details of the experimental setup can be found in our research paper listed as reference [15].

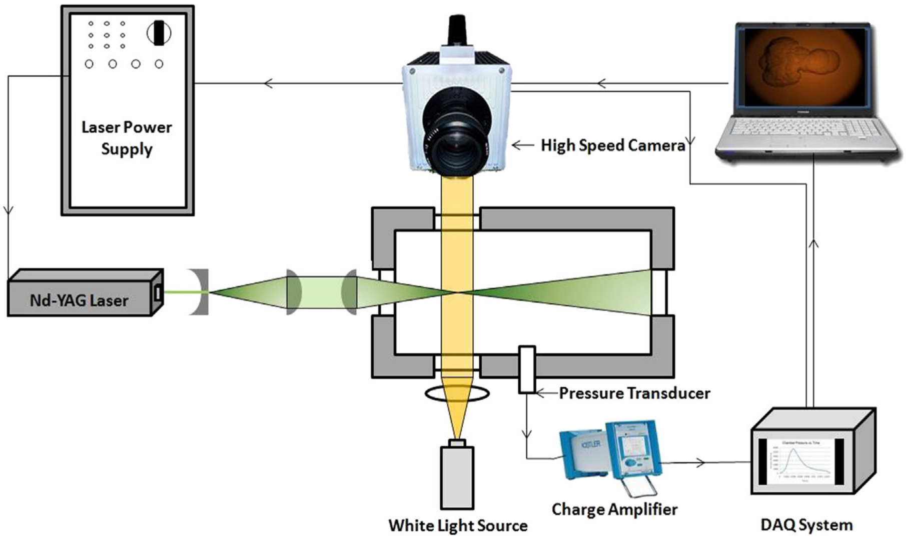

Fig. 1 – Experimental setup for laser ignition of hydrogen–air mixtures.

To perform laser ignition and visualizing of the flame kernel evolution, CVCC was designed and fabricated with four optical windows located diametrically opposite, two along the cylindrical axis and two on the opposing chamber walls. First pair of windows was used for focusing the laser beam into the CVCC, while the second pair was used for visualizing the flame kernel evolution with time. Laser beam was focused into the CVCC using a series of optical components. Anti-reflective film coated lenses and windows were used to reduce the energy losses during beam propagation. The optical setup was aligned in a way such that plasma formation and flame kernel evolution took place at desired spatial position, in order to be able to visualize it through the second pair of windows. Shadowgraphy technique was used for visualizing flame kernel evolution. Flame kernel was illuminated using a white light source (Thorlabs; OSL 1-EC). White light from the source was collimated using a 100 mm focal length converging lens for superior illumination. The flame kernel development and evolution were then captured using a high speed camera (Photron; SA 1.1) operated at 54000 fps.

In-cylinder pressure variations during the combustion process were measured using a piezoelectric pressure transducer (Kistler; 6052C). Signals from this pressure transducer were amplified using a charge amplifier (Kistler; 5015) and then acquired by a high speed combustion data acquisition system (Hi-Technique; meDAQ) at 1 kHz sampling frequency. It was ensured that the initial experimental conditions were identical for all experiments reported in this study.

3. Results and discussion

Experiments were performed on hydrogen–air mixtures in the CVCC at 373 K temperature and 10 bar initial chamber filling pressure. The relative air–fuel ratio (λ) was varied from $\lambda = 2.0$–5.0 during the experimental investigations. The experiments were limited to $\lambda = 2.0$ due to very fast pressure rise rates observed inside the CVCC, which compromised safety of sapphire windows.

3.1. *Pressure–time history*

The focus of the study was to judge the applicability of laser ignition to ultra-lean air–fuel mixtures of hydrogen. During this investigation, an air–fuel mixture upto $\lambda = 8.0$ could be successfully ignited. However due to limited resolution of piezoelectric pressure transducer, ignition of further leaner mixtures could not be verified.

Fig. 2 shows the in-cylinder pressure–time history for different mixtures of varying λ. From the Figure, it can be clearly seen that as λ increases (i.e. the mixture becomes leaner), the peak pressure in CVCC decreases. The highest excess pressure was observed for $\lambda = 2.0$ (33.13 bars), which was also the richest mixture investigated in the present study. While the lean limit reported in this study was chosen to be $\lambda = 5.0$, because for this mixture, the excess pressure rise recorded was as low as 0.36 bars. For $\lambda > 5$, it was observed that though the combustion takes place, the excess pressure rise in the chamber was extremely low. For $\lambda = 2.5$–3.0, an oscillating pressure wave was

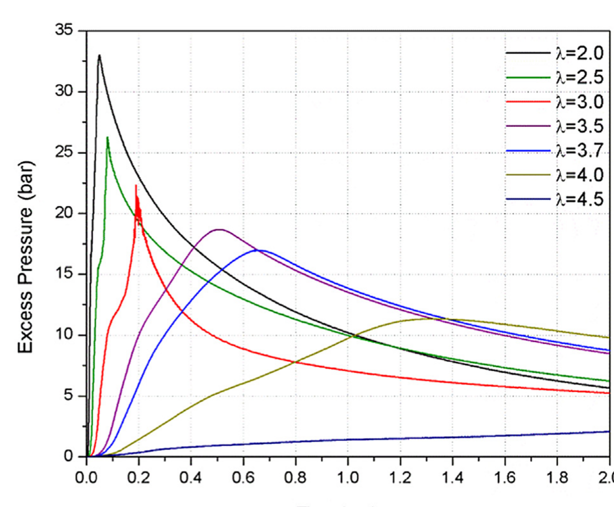

Fig. 2 – Pressure–time history of CVCC for varying λ.

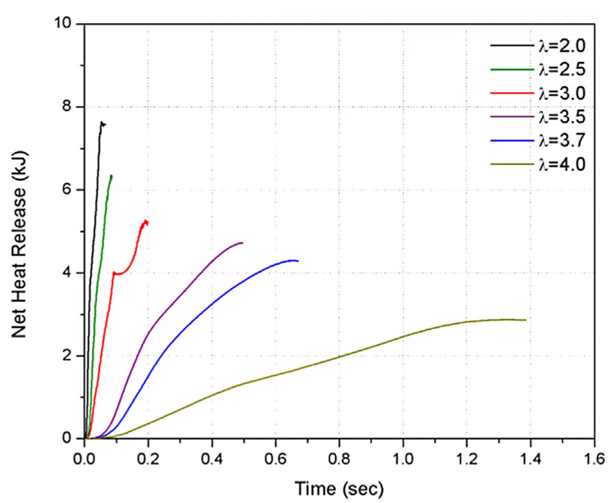

Fig. 3 – Net heat release vs. Time for varying λ.

recorded near the peak of pressure–time curve. These oscillations were due to auto ignition of hydrogen–air mixture, possibly caused by high temperature and pressure conditions prevailing in the CVCC. The shock waves produced from the auto-ignition were reflected by the walls which produced oscillations in the pressure traces [12]. This auto ignition behavior of the mixture is also be termed as 'Knocking', which is dangerous for engine applications from structural safety perspective.

It can also be concluded from Fig. 2 that as the fuel–air mixture become leaner, rate of pressure rise decreases, leading to slower flame velocity. This means that for higher λ, time taken for completion of combustion was higher compared to the time taken for lower λ. Two-stage combustion was also observed from the pressure–time history for $\lambda = 2.5–3.0$. Such results were also observed by Tanaka et al. [16] and Weinrotter et al. [12]. They predicted the formation of H_2O_2 molecules, which remain inactive at a specific pressure. As this specific pressure is attained, these molecules dissociate into highly reactive OH^- radicals thereby increasing the heat release significantly.

It is important to carry out the heat release analysis for the CVCC. For this, laws of thermodynamics have to be applied to the CVCC and a series of assumption have to be made in order to simplify the analysis. The following assumptions were made for the heat release calculations of the hydrogen–air mixture combustion in the CVCC.

I.The cylinder charge was considered to be an ideal gas.
II.Thermodynamic properties of the combustible mixture inside the combustion chamber were uniform.
III.Dissociation of combustion products was neglected.
IV.Heat transfer from the combustion chamber walls was neglected.

Heat release rate in the CVCC was calculated by the following equation [17]:

$$\frac{dQ}{dt} = \left(\frac{1}{\gamma - 1}\right) V \frac{dP}{dt} + \left(\frac{\gamma}{\gamma - 1}\right) P \frac{dV}{dt}$$

Here Q is net heat release; t is time; V is volume of the CVCC; P is pressure; and γ is the heat capacity ratio. It is assumed that the value of γ remains constant. In this study, experiments were performed in a CVCC, whose volume does not change with time therefore the second term in this equation becomes zero. Therefore:

$$\frac{dQ}{dt} = \left(\frac{1}{\gamma - 1}\right) V \frac{dP}{dt}$$

The final equation for calculating net heat release therefore becomes:

$$Q = \int_0^t \left(\frac{dQ}{dt}\right) dt$$

Fig. 3 shows the variation of net heat release (KJ) with time for varying λ of hydrogen–air mixture. It shows that the net heat release for relatively richer hydrogen–air mixtures (lower λ) is higher compared to leaner mixtures (higher λ). This result resembles with the results obtained in Fig. 2. From

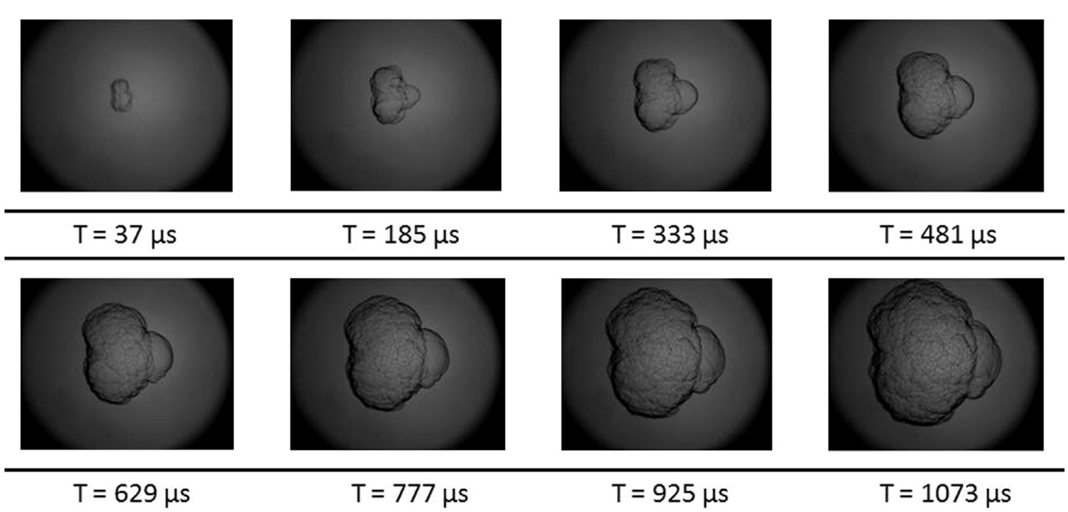

Fig. 4 – Shadowgraphs of flame kernel evolution for hydrogen–air mixture (λ = 2.0).

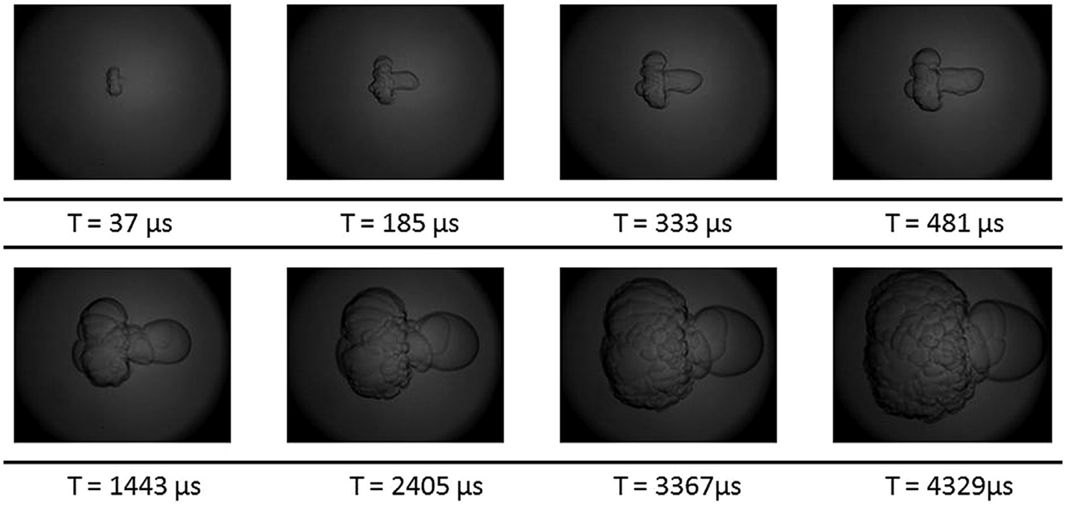

Fig. 5 – Shadowgraphs of flame kernel evolution for hydrogen–air mixture (λ = 3.0).

Fig. 3, it can be noted that for $\lambda = 2.5–3.0$, net heat release first rises, then becomes constant before starting to rise again. This shows two-stage combustion in the fuel–air mixture, which is also depicted in Fig. 2.

3.2. *Flame kernel evolution*

Flame kernel evolution was recorded for different λ (2.0–5.0) using Shadowgraphy technique. The images recorded were 1.45 cm long and 1.15 cm high and were recorded at an equi-spaced interval of 18.5 µs between two consecutive image frames, which were captured by the high speed camera operating at 54000 fps. These images were analyzed to obtain the shape and growth rate of flame kernel spatially and temporally. The growth of flame kernel for varying λ is illustrated through eight images in Figs. 4–6. The first four images indicate the flame kernel growth after 37 µs, 185 µs, 333 µ and 481 µs respectively after the plasma generation, in order to compare relative growth rates of flame kernel in same time duration. The next four images exemplify full growth/evolution of flame kernel in different time intervals. The entry of laser beam is from the right of all the shadowgraphs for all experiments. Figs. 4–6 depict the flame kernel evolution process for $\lambda = 2.0–4.0$ respectively.

A typical laser ignition induced flame kernel in the form of combination of toroidal structure with a front lobe is observed [8]. Bradley et al. [18] attributed the evolution of mushroom shaped flame kernel to two shockwaves; one toroidal and other longitudinal. Srivastava et al. [11] suggested that toroidal shock waves initially had an ellipsoidal shape caused by asymmetric energy deposition of the laser pulse. At a later stage, when it propagated outwards, the shockwaves were found to approach a spherical geometry with an elongated flame front towards the laser beam.

It is observed that for λ = 4.0, it took 8473 µs for the formation of fully grown flame kernel, which is 8 times as

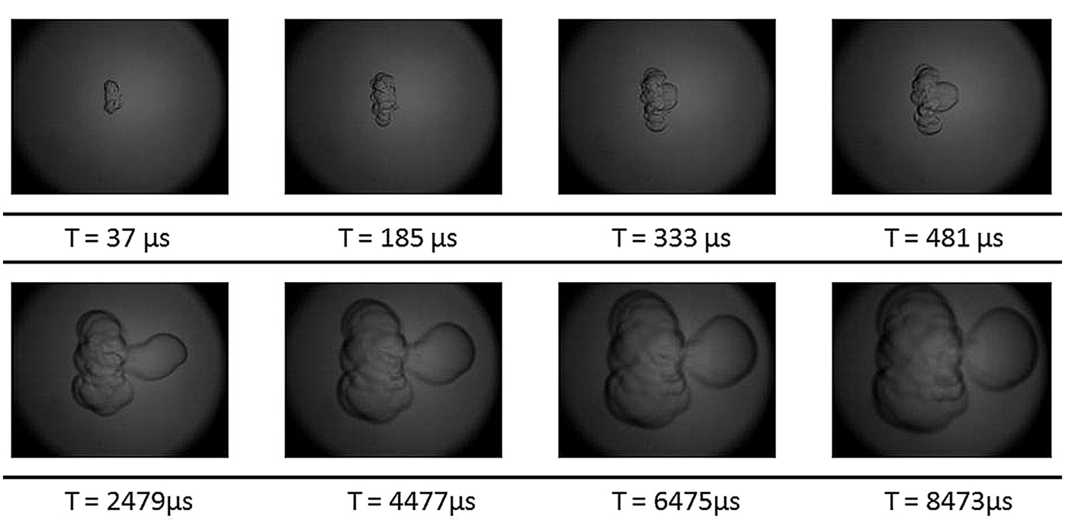

Fig. 6 – Shadowgraphs of flame kernel evolution for hydrogen–air mixture (λ = 4.0).

compared to 1073 μs taken for the formation of fully grown flame kernel at $\lambda = 2.0$. Therefore it can be concluded that as the fuel–air mixture becomes leaner, rate of flame kernel growth decreases and the time taken for evolution of fully grown flame kernel increases. In our earlier research, Srivastava et al. [5] observed similar trends of flame kernel evolution for CNG-air mixtures also.

The flame kernel growth is affected by two factors. It is primarily because of the flame kernel growth in the combustible mixture and it is also affected by the volumetric expansion of the hot gases inside the plasma, however this effect remains rather limited. For the sake of simplicity of analysis, volumetric expansion of the hot gases inside the plasma are neglected, and the flame kernel growth rate in different directions is referred as flame speed for sake of comparison. An image analysis was performed to analyze the growth rate and temporal variation of flame kernel. In this study, growth of flame kernel was measured along four different directions. The direction of laser beam travel and its opposite were termed as negative X and positive X direction respectively. These directions are denoted by X− and X+ in the results. The directions perpendicular to the laser beam in the plane of imaging were represented by Y+ and Y−. The growth of flame kernel for different λ were compared for the same flame propagation distance (7.25 mm in X+ direction and 6.6 mm in X− direction) to get a better insight into flame kernel growth rates in these directions. The displacement along each direction was calculated from the flame kernel centroid of the first image frame since the variation in the centroid position in various image frames is negligible. For each dataset, multiple experiments were performed and an average of atleast 20 experiments was reported in order to reduce the experimental error.

Flame propagation distances were compared for different λ in the direction of laser beam propagation (X−) in Fig. 7(a). Figure shows that as the mixture become leaner, the flame propagation distance decreases. For $\lambda = 2.0$, the flame takes approximately 1580 μs to propagate 6.6 mm in X− direction. This increased to 3065 μs for $\lambda = 2.5$ and 4720 μs for $\lambda = 3.0$. It was also observed that flame propagation distance increased rapidly during the early stages of flame kernel evolution, suggesting higher flame speeds initially. For leaner mixtures ($\lambda = 3.5$, 4.0 and 4.5), flame propagation distance in X− direction decreased with time in the later stages of combustion because leaner mixtures were unable to sustain the combustion beyond a limit, resulting in reduced flame speed. However for mixtures with $\lambda = 2.0$, 2.5, and 3.0, flame propagation distance increased at a much higher rate.

Flame kernel propagation in the direction opposite to laser beam (X+ direction) is shown in Fig. 7(b). It can be seen from this Figure that propagation of flame kernel varies almost linearly for lower λ (2.0 and 2.5) w.r.t. time, which suggests almost constant flame velocity. It can also be concluded that propagation distance of flame kernel in X+ (opposite to laser propagation) was higher than the propagation distance of flame kernel in X− (along the laser propagation) direction, for all values of λ. Fig. 7(c) shows the propagation of flame kernel for different fuel–air mixtures in Y+ direction. Since the propagation of flame kernel in Y+ and Y− direction was identical, therefore only one direction is reported in this paper. The trends are similar to the one observed for the X directions

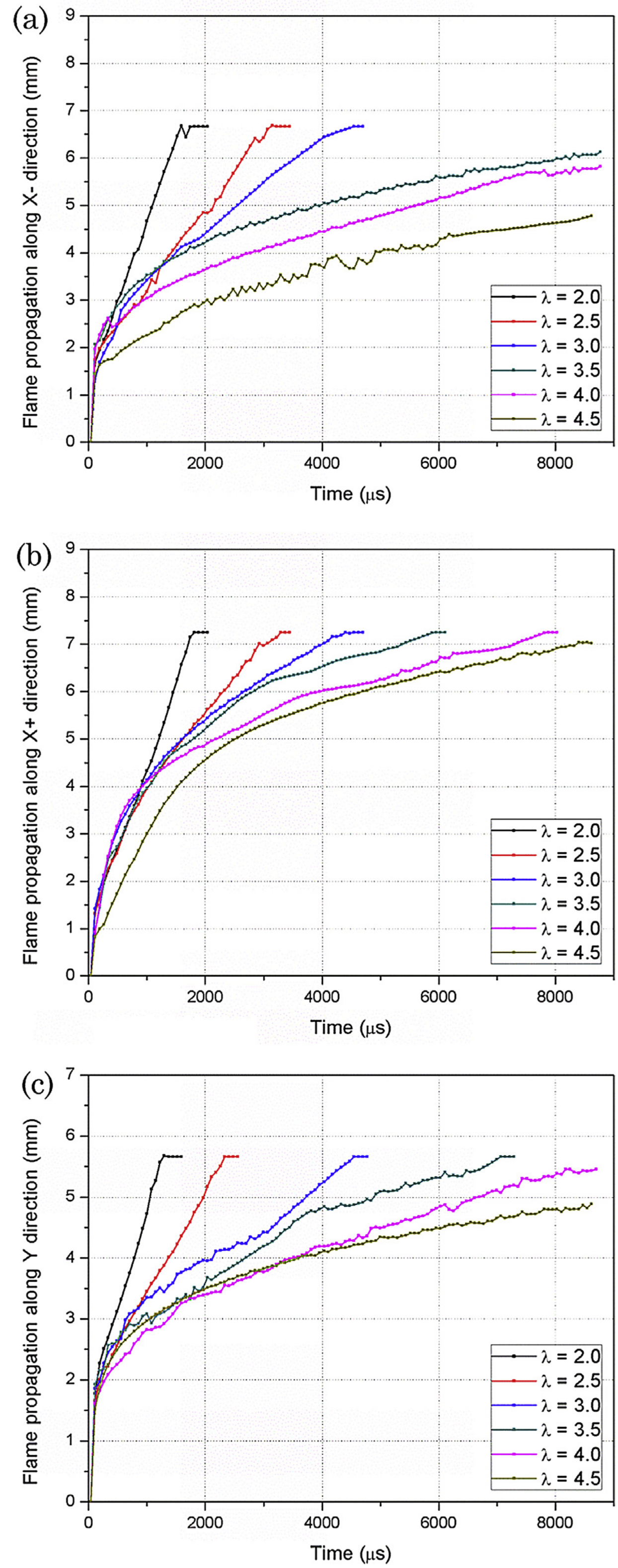

Fig. 7 – Temporal variation of flame kernel propagation (a) direction of opposite to laser beam propagation (X− direction) (b) direction of laser beam propagation (X+ direction) (c) orthogonal to the laser beam propagation (Y direction).

reported earlier. The rate of flame propagation decreased on moving towards leaner mixture regime, suggesting that overall volumetric growth rate of flame kernel reduced on moving towards leaner fuel–air mixtures. Flame propagation variation was an almost linear function for $\lambda = 2.0$ and 2.5, however its rate reduced with time for leaner fuel–air mixtures.

The data relates with what has been actually observed in the flame kernel visualization. It was observed that plasma growth took place 'towards the incoming laser beam' much faster compared to 'along the laser beam'. The reason for this reverse propagation of plasma is that the layers of gas outside the plasma, although transparent to the laser beam, were heated by the plasma radiations. This outside gas close to the plasma in-turn was ionized to such an extent that it strongly absorbed the laser beam [19]. As a result, these gas layers were heated further very quickly and their temperatures increase. By this time, another layer of plasma near the laser became strongly absorbing, hence the boundary of plasma starts moving towards the focusing lens.

The variation of the flame speed for different λ in X– direction is shown in Fig. 8. The flame speed is observed to decrease exponentially with time. Similar results are observed for other directions as well. Combining these results, it can be inferred that as the fuel–air mixture becomes leaner, flame speed decreases spatially. This effect was also observed and supported by the results obtained in the pressure–time history diagrams. It was observed that hydrogen–air mixtures can be ignited to significantly leaner limits using laser-ignition. This limit and the minimum laser pulse energy required for ignition could be stretched further by using better quality lasers and optics.

3.3. Minimum ignition energy

Minimum laser pulse energies required to ignite various combustible mixtures of different λ at 10 bar chamber filling pressures are given in Table 1. It can be seen from this table that Minimum pulse energy required for laser ignition increases with increasing λ. Energy required to ignite the mixture successfully with $\lambda = 2.0$ was 9.78 mJ/pulse, and it increased to 14.66 mJ/pulse for mixture with $\lambda = 5.0$.

There is significantly higher laser pulse energy required for ignition of the mixture at $\lambda = 5.0$ compared to $\lambda = 4.0$. This may be due to the fact that the mixture with $\lambda = 5.0$ is closer to the lower flammability limit under the given experimental conditions. On approaching the lean limit of combustibility, number of fuel molecules in the focal spot volume reduces; hence larger amount of energy would be required to produce sufficient number of free electrons and radicals to generate plasma. Therefore higher pulse energy was required to ignite leaner mixtures.

Table 1 – Minimum laser pulse energy required for successful ignition of hydrogen–air mixtures at 10 bar initial chamber filling pressure.

Relative air–fuel ratio (λ)	Minimum laser pulse energy required for ignition (mJ/Pulse)
2.0	9.78
2.5	10.27
3.0	10.60
3.5	11.18
4.0	12.40
5.0	14.66

Fig. 9 compares the pressure–time history for combustion of hydrogen–air mixture at 10 bar initial chamber filling pressure for standard laser pulse energy (14.66 mJ/pulse) as well as minimum ignition energy for different λ (2.0–3.7). It is observed that at minimum laser pulse ignition energy, the flame speed is slightly lower as compared to the one observed with standard pulse energy. Also, the peak pressure decreases slightly during operation with minimum ignition pulse energies (Fig. 10). However, the reduction in this pressure rise is less than 5%, therefore it can be ignored. Fig. 10 compares the time taken to attain peak chamber pressure after firing the laser pulse with standard pulse energies vis-a-vis minimum ignition pulse energies. The minimum ignition pulse energy could be further lowered by improving the laser beam quality i.e. by reducing the M^2 value of the laser beam and by using superior quality aberration-free converging lens and optics.

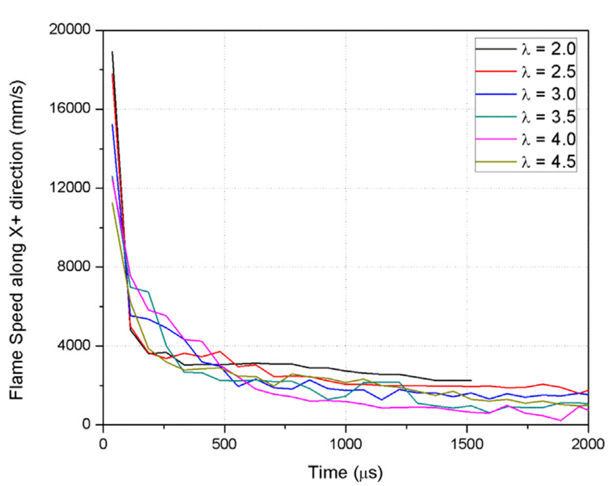

Fig. 8 – Flame speed in X– direction.

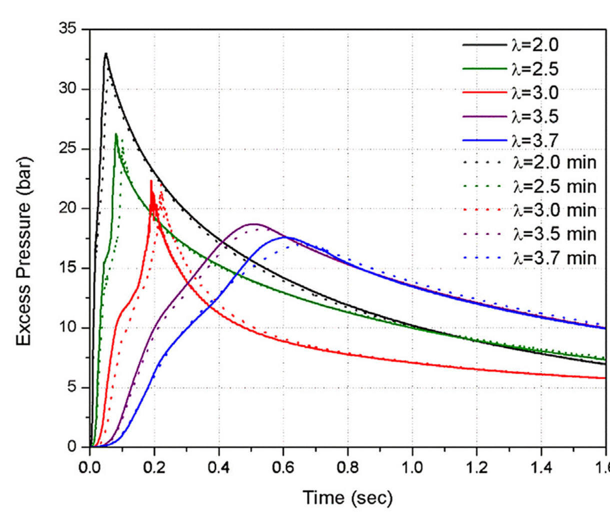

Fig. 9 – Excess pressure comparison between standard pulse energy and minimum ignition pulse energy.

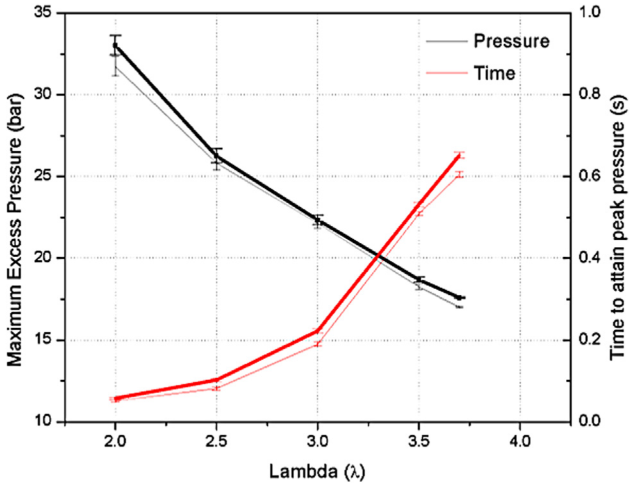

Fig. 10 – Comparison of maximum pressure rise and time taken to attain peak cylinder pressure for standard pulse energy and minimum ignition pulse energy.

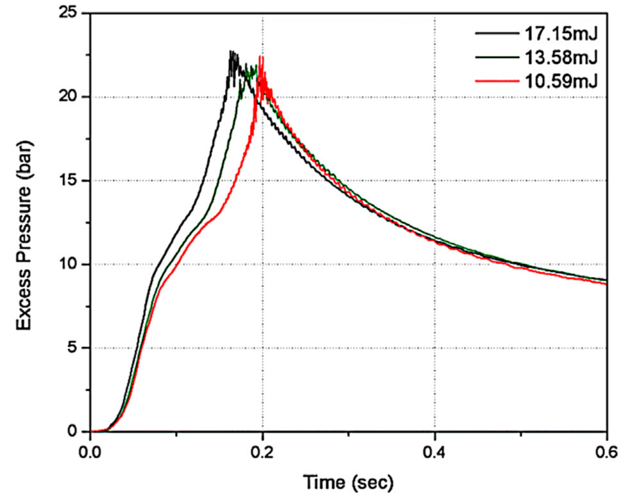

Fig. 11 – Comparison of chamber pressure rise for different laser pulse energies at $\lambda = 3.0$ and 10 bar initial chamber filling pressure.

3.4. *Effect of laser pulse energy*

Effect of laser pulse energy on the combustion of hydrogen–air mixture was investigated at a constant λ using three different laser pulse energies. The initial chamber filling pressure and temperature were maintained identical during all the experiments. The laser pulse energy was varied from 10.59 mJ to 17.15 mJ and the effect of variation in laser pulse energy on the pressure–time history and flame speeds were investigated. Kopecek et al. [20] investigated the effect of laser pulse energy in methane–air mixtures and concluded that on increasing the laser pulse energy, higher peak cylinder pressures were observed and the combustion duration was shortened. Similar experiments on hydrogen–air mixtures combustion in CVCC were also conducted by Weinrotter et al. [12] however they concluded that there was no significant effect of laser pulse energy on both, the peak chamber pressure and the combustion duration.

It can be observed from Fig. 11 that for higher laser pulse energies, shorter combustion duration could be realized. At lower laser pulse energy of 10.59 mJ, the time taken to attain peak chamber pressure was 201 ms, and for higher laser pulse energy of 17.15 mJ, this duration reduced to 168 ms. As the laser pulse energy increases, the energy density in the focal volume also increases. Higher energy plasma generates stronger and faster shockwaves, which shorten the combustion duration. However, no significant change in peak chamber pressures was recorded during these investigations.

4. Conclusions

Laser ignition of hydrogen–air mixture was investigated in a CVCC and λ was varied from 2.0 to 5.0 under identical initial operating conditions. Flame kernel evolution and pressure–time history were recorded and analyzed for different λ. Results showed that as λ increased from 2.0 to 5.0, the peak cylinder pressure and rate of pressure rise decreased. Oscillations were observed in the pressure–time curves for $\lambda = 2.5$ and 3.0 due to knocking caused by auto-ignition of hydrogen–air mixtures, in addition to two-stage combustion. Net heat release also decreased with increasing λ.

Flame kernel evolution was visualized using shadowgraphy. It was observed that the flame speed decreased with increasing λ in all directions. Also, a large number of wave fronts were observed on the toroidal surface of the flame kernel for richer fuel–air mixtures as compared to leaner mixtures, directly affecting the intensity of explosion. Minimum laser pulse energy required to ignite hydrogen – air mixture increased on increasing λ. It was also observed that on increasing the laser pulse energy, time taken to attain peak cylinder pressure reduced slightly, indicating faster flame speeds in hydrogen–air mixtures, however the peak cylinder pressure remained almost constant.

Laser ignition therefore proved to be a potential enabling technology in realizing the dream of a practical hydrogen fuelled engine.

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