Laser Ignition of Hydrogen-Air Mixture in a Combustion Bomb

Dhananjay Kumar Srivastava, Avinash Kumar Agarwal*
Engine Research Laboratory
Department of Mechanical Engineering, Indian Institute of Technology Kanpur
Kanpur - 208016, India

Ernst Wintner
Photonics Institute, Technical University of Vienna, Austria

*Corresponding Author’s email: akag@itk.ac.in

ABSTRACT

Due to the demands of the market to increase efficiency and power density of large MW size gas engines, existing ignition schemes are gradually reaching their limits. These limitations initially triggered the development of laser ignition as an effective alternative, first only for gas engines and now for a much wider range of internal combustion engines revealing a number of immediate advantages like no electrode erosion or flame kernel quenching. Within this broad range investigation, laser plasmas were generated by ns Nd-YAG laser pulses and characterized by emission and Schlieren diagnostic methods. High-pressure chamber experiments with lean hydrogen-air mixtures were successfully performed and allowed the determination of essential parameters like minimum pulse energies at different ignition pressures and temperatures as well as at variable fuel air compositions. In this way, relevant parameters were acquired allowing estimation/development of future laser ignition systems. It is expected that laser ignition involving such novel solid-state lasers will allow much lower maintenance efforts.

Key Words: Laser Ignition, plasma, combustion, engine, emission imaging, flame kernel.

INTRODUCTION

Advancing the state of 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 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.

As a matter of fact, excellent efficiencies of internal combustion engines - in the first place of gas engines - of presently close to 46% are only achievable if highest mean pressures are applied. This requires remarkable technical improvements in general, and especially with respect to the ignition system employed. With conventional spark ignition, a limit around 2.5 MPa is observed. Figure 1 shows the dependence of required spark voltage versus BMEP for two different degrees of leanness yielding 500 mg NO/Nm³ or 250 mg NO/Nm³ (leaner air/fuel mixture). This dependence can be easily understood on the basis of the well known increase of breakthrough voltage versus pressure. It is impossible in practical operation to raise the spark voltage beyond 35 kV, and this is associated with a considerable reduction of lifetime.

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 NOx emissions
• 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 [1,2,3]

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 minimize the service requirements. A diode-pumped laser ignition system has potential lifetime up to 10,000 hours compared to spark plug lifetimes of the order of 2000 to 4000 hours [Source: GE 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 again shortens the total combustion duration significantly.

PRINCIPLE OF LASER IGNITION

The behavior of combustion of gaseous media, especially inside an internal combustion engine, is strongly influenced by the kind of ignition source being applied. There are a lot of similarities between laser and conventional spark plug ignition, like for example the spatially limited ignition volume, the plasma generated by an electrical breakdown inside the medium, but also many crucial differences like different time scales of the energy transfer period (several nanoseconds in the case of the laser compared to several hundred microseconds for spark plugs) and the influence of quenching surfaces like electrodes. The following part should summarize the peculiarities of laser ignition. The most dominant plasma producing process is the electron cascade process: Initial electrons absorb photons out of the laser beam via the inverse bremsstrahlung process. If the electrons gain sufficient energy, they can ionize 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 (dust-, aerosols- and soot-particles) [4] which absorb the laser radiation and lead to high local temperature and in consequence to free electrons starting the avalanche process. In contrast to multiphoton ionization (MPI), no wavelength dependence is expected for this initiation effect [5]. It is very unlikely that the first free electrons are produced by multiphoton ionization because the intensities in the focus (10^{10} W/mm^2) are too low to ionize gas molecules via this process, which requires intensities of more than 10^{12} W/mm^2 [6,7].

EXPERIMENTAL SETUP

In this part of the work, experiments in a pressure chamber of constant volume were performed to investigate the main characteristics of laser ignition under high pressure and high temperature conditions for the requirement of an internal combustion engine. One major drawback of such experiments is that the gas flow conditions inside the cylinder of an engine cannot be simulated leaving the important question about the performance of the ignition source under such circumstances with no answer.

As a first step towards a systematic investigation of laser ignition, the condition for forming a laser excited plasma were studied. A Q-switched Nd:YAG laser 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 was used in this experiments. The beam diameter was 5.7 mm (1/e^2) with a beam quality of M^2 < 2. The laser plasma in laminar air flow at atmospheric condition (laser pulse energy of 20mJ) was measured. A best-form lens with a focusing length f = 50 mm was used for focusing the laser beam. Figure 2 shows the experimental setup for measurement of laser plasma observing the near ultraviolet spectrum of the emitted radiation with 3 ns temporal resolution.

For all experiments, compressed air (water 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. The maximum filling pressure was 3 MPa and the chamber was heated up to an initial temperature 423 K for each combustion attempt.

RESULTS AND DISCUSSIONS

Plasma Measurement

In many ways, the laser-sustained plasma is similar to direct current arcs that are operated in similar gases and at similar pressures. However, the laser plasma will generally be more compact and have a higher maximum temperature than other continuous arcs sources and can be sustained in a steady state well away from containing boundaries. A fundamental difference in the way in which energy is observed by the plasma is responsible for these unique characteristics of the laser plasma.

The first image of the plasma appeared 6 ns after the starting of laser pulse. 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 (away from the focusing lens). After a certain delay, the plasma becomes strongly absorbing for the laser beam and it expands out of the focal volume in combination with a shock wave. After the laser pulse duration, plasma starts to become hotter and at 30 ns it had the maximum emission intensity. The maximum diameter and length of the laser plasma at 30 ns was 0.01 mm and 0.27 mm, respectively as it is depicted in Figure 3. The plasma emission last about 80 ns after the laser pulse.

Fig. 1: Breakdown voltage of the spark plugs of a large gas engine depending on BMEP (break mean effective pressure) and NOx emissions.

Fig. 2: Experimental setup for measurement of laser plasma with the spontaneous emission technique

Fig. 3: Emission of the laser plasma (λ = 330 nm) 30 ns after the laser pulse of 20 mJ pulse energy, laser beam entering from right to left.

Combustion Results

Fig. 4 shows the dependence of the minimum pulse energy needed for ignition (MPE) depending on relative air-fuel ratio A/Frel and initial pressure for hydrogen-air mixtures. By employing a conventional lens system of NA = 0.046 and focusing the beam down to a spot size of about 29 μm, the MPE for hydrogen-air mixtures of A/Frel = 2 was measured. It is continuously increasing with increasing content of air over the whole mixture range being measured.

Fig. 4: Minimum laser pulse energy needed for ignition (MPE) of hydrogen-air mixtures

Fig. 5: Pressure history in the combustion chamber after laser ignition (laser pulse energy 20 mJ at λ = 2.5-3.5, initial chamber pressure = 3 MPa, initial chamber temperature = 323 K).

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Fig. 6: Pressure history in the combustion chamber using spark plug ignition, ($\lambda = 2.5$-3.5, initial pressure and temperature was 3 MPa and 323 K, respectively.

It can be observed that with leaner mixtures and decreasing initial pressures the MPE needed to ignite the mixture increased. With higher pressures the number of molecules in the focal region is increased and the laser beam can be absorbed more sufficiently in the gas. Moreover, with leaner mixtures the number of H$_2$ molecules and therefore the number of H-radicals produced through the plasma is decreased, making ignition less sufficient, and that is why more energy is needed to ignite the mixture. Figure 5 depicts a pressure history of combustions for different mixtures ($\lambda$) at an initial chamber temperature of 323 K and an initial pressure of 3 MPa. As expected, the peak pressure decreases with leaner mixtures. Excess pressure for $\lambda = 2.5$ is 8.3 MPa where as, for $\lambda = 3.5$, excess pressure is 4.0 MPa. Also, a clear trend of longer combustion times with leaner mixtures could be observed, which is explained in the faster flame velocity of richer gas mixtures [8,9]. The time till the peak pressure is reached varied from 22 ms ($\lambda =2.5$) to 580 ms ($\lambda =3.5$).

Figure 6 shows pressure rise with time, when mixtures were ignited by spark plug (GE Jenbacher P7: spark gap of 0.35 mm and coil energy of 180 mJ) keeping same initial experimental condition. It can be seen that peak pressure in both cases (i.e. laser ignition and spark plug ignition) are comparable. The time of pressure rise in case of laser ignition is shorter. This may be because of absence of flame quenching in case of laser ignition. Also, a clear 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.

CONCLUSIONS

Laser ignition of hydrogen–air mixtures was investigated in a constant volume chamber. Laser generated plasmas were measured in air by emission photography yielding detailed geometrical parameters. The size and position of the plasma in the combustion chamber are very important factors for ignition and combustion. If the plasma size is enlarged the total combustion time decreased however the MPE increased. The total combustion time decreased if the plasma is positioned in the centre of the combustion chamber.

A very interesting fact being potentially very useful for practical applications is, that with higher initial pressures the minimum laser pulse energy (MPE) for ignition is decreasing in contrast to the conventional spark plug where the energy for an ignition spark with increasing initial pressure is increasing to an upper limit. MPE was found to vary between 1 and 7 mJ for the conditions tested.

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Contact

Dr. Avinash Kumar Agarwal is currently working as Assistant Professor of Mechanical Engineering at Indian Institute of Technology, Kanpur since March 2001. He is a 1994 Mechanical Engineering graduate from MREC Jaipur. His area of doctoral research was developing biodiesel and related engine tribology investigations. Dr Agarwal joined Engine Research Center, University of Wisconsin, Madison, USA for pursuing his Post-Doctoral research from August 1999 – February 2001. His main areas of current interest are combustion phenomenon study in IC engines, automobile emissions, biodiesel development and characterization, laser diagnostic techniques, PIV, lubricating oil consumption phenomenon, lubricating oil tribology, development of micro sensors, alternative fuels for diesel engines etc.

Dhananjay Srivastava is a Graduate student working with Dr. Agarwal on his doctoral dissertation in mechanical engineering from IIT Kanpur. He is a graduate of production engineering from BIT, Sindri (2001) and he completed his Master’s in Material Science from IIT Kanpur in the year 2004. His areas of interest include Internal Combustion Engines, Laser Ignition, emission control and combustion.

Ernst Wintner, after having completed a thesis in metallurgy, received his PhD (Physics and mathematics) in 1976 with special distinction (sub
auspicis) from the University of Vienna. Thereafter he joined Vienna University of Technology (VUT), changing to the field of photonics. His scientific work comprises nonlinear optics, fiber optic sensors, solid-state lasers, ultrashort pulse generation, and their applications, e.g., to materials processing and medicine, and finally color fading in art collections. Dr. Wintner is a professor at the Photonics Institute of VUT.