

# Study of flame development in 12% methane-air mixture ignited by laser

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A comparative study of ignition realized by a classical spark plug and by a Nd:YAG laser in 12% methane-air mixture was performed. Various parameters of the ignition, such as the peak pressure, the pressure building time, or the speed propagation of the flame front were recorded at various initial filling pressure of the combustion chamber, or function of the laser pulse energy. Advantages of ignition by laser in comparison with classical ignition by an electrical spark plug are discussed.

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## 1. Introduction

Internal combustion engines are very important in the transportation and energy production domains. In last decades great effort was done for reducing the pollutant emissions caused by vehicles with internal combustion engines, because it has a large impact on the environment. The reduction of NO<sub>x</sub> is mainly influenced by the ignition process, which is a complex phenomenon known to strongly affect the subsequent combustion. The ignition method used in internal combustion engines changed little in the last few-tens of years, but using a laser-based ignition source has been envisaged for some time [1-4]. Consequently, ignition induced by laser radiation was tested on different types of fuel, such as methane-air mixtures [2, 5], methane-hydrogen-gas mixtures [6-9], propane, dodecane or jet fuel [10], or on a real automobile engine [11-13].

Replacing the conventional electric spark plug with a laser-induced igniter can provide several advantages. For example, ignition of lean fuel/air mixtures is possible: This brings environmental benefits because the NO<sub>x</sub> emissions are reduced. Moreover, location of ignition may be freely chosen by focusing the laser, whereas the quenching effects produced by the electrical spark plug are absent. Furthermore, the lifetime of a laser ignition system is expected to be longer than that of a spark plug, because erosion effects don't appear. Despite of these advantages, a drawback of a laser igniter is the system size, which has to be reduced to that of a spark plug. This drawback can be overcome by developing compact, diode-pumped, passively Q-switched Nd:YAG /Cr<sup>4+</sup>:YAG micro-lasers that can yield laser pulses with high energy and short duration in a beam of good quality [12-15].

The early stages of flame formation have strong implications on pollutant formation and flame propagation. Interaction of laser radiation with the gas mixture realizes the gas breakdown. There are four types of laser-gas interaction that produces breakdown: thermal

breakdown, photochemical ignition, resonant breakdown and non-resonant breakdown. Thermal breakdown means that energy given by laser is absorbed by the gas mixture through translational, vibration or rotational modes of the molecules. As a result, molecular bonds are broken and chemical reactions occur. In photochemical ignition, the photons dissociate the target molecules into reactive radical species. If the production rates of these radicals are greater than their recombination rates the process of ignition starts leading to full-scale combustion. The process of resonant breakdown involves non-resonant multi-photon photo-dissociation of some molecules in the gas mixtures followed by resonant photo-ionization of atoms generated by the photo-dissociation process. Non-resonant breakdown starts with the multi-photon ionization of a number of the gas molecules. These molecules release electrons that are absorbing photons out of the laser beam via the inverse 'bremsstrahlung' process [3]. The electrons are increasing their kinetic energy and ionize other gas molecules on impact, leading to an electron avalanche and gas breakdown. This process requires initial seed electrons produced from impurities in the gas mixture (dust, aerosols) that are interacting with optical pulses of high intensities ( $\sim 10^{12}$  W/cm<sup>2</sup>). A well localized plasma with temperatures in the order of 10<sup>6</sup> K and pressures in the order of 10<sup>2</sup> MPa results after ignition. The early stages of flame development inside the explosion chamber are therefore crucial in getting high efficiency and low pollutants content.

In this work we performed a comparative investigation of ignition obtained by a classical electrical spark plug and by a laser in a 12% methane-air mixture gas. The shadowgraph method was used to visualize the early stages of the ignition process, and to evaluate some parameters of the ignition, such as the peak pressure, the pressure building time, or the speed propagation of the flame front. Variation of these parameters with initial filling pressure of the combustion chamber, or of the laser pulse energy is determined.

## 2. Experimental conditions

The experimental setup used for the ignition experiments is shown in Fig. 1. The ignition was studied in a constant-volume chamber, with dimensions of  $140 \times 140 \times 140 \text{ mm}^3$ . The chamber was constructed to withstand pressures over 100 MPa, and therefore the ignition can be safely investigated up to 0.5-MPa filling pressure. The chamber was equipped with four BK7 glass rectangular ( $100 \times 100 \text{ mm}^2$ ) windows, which were built such to allow recording of flame kernel development by shadowgraph method [16]. One window serves as input for the laser beam, having a focusing lens placed closed of it. The chamber was equipped externally with several ports, for gas supply and gas outlet, for a pressure sensor, as well as for safety-pressure valve. The pressure developed during ignition was measured with a piezoelectric pressure transducer (PCB 112B10 type) mounted on a spark plug-like adaptor (PCB 65 A). The signal from the sensor was amplified with a charge amplifier (PCB 422E13) and recorded by a computer.

The gas used in experiments was 12% methane-air mixture: This choice was justified by the fact that laser pulse energy necessary for ignition was low at this concentration [3]. The laser ignition was realized with an electro-optical Q-switched Nd:YAG laser that delivered pulses with energy ranging between 12 and 23 mJ at the wavelength of 1064 nm, and duration (FWHM definition) of  $\sim 8 \text{ ns}$ . The laser beam was focused into chamber with a lens with a 75-mm focal length, to spot size of  $70 \mu\text{m}$  in diameter. Conventional ignition was realized with a modified spark plug, such as position of ignition was close to the chamber center. This arrangement allows recording of flame kernel generation and propagation in the combustion chamber.

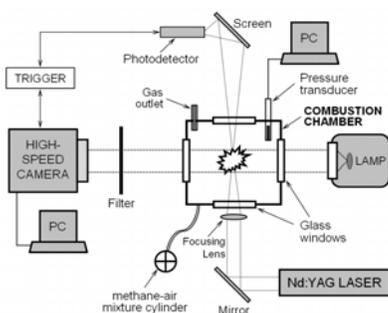


Fig. 1. The experimental set-up used for ignition induced by laser and recording of flame development.

The light source for shadowgraph recording was a xenon lamp that was positioned perpendicularly to the direction of the laser beam. The flame development was recorded with a Photron FASTCAM 1024 PCI digital video camera at 3000 frames per second and  $512 \times 512$  pixels resolution. A fast photodiode was used to synchronize recording with the ignition time.

## 3. Experimental results and discussion

Fig. 2 shows flame photographs of the two types of ignition for the 12% methane-air mixture gas. In the case

of spark-plug ignition it can be seen that the flame kernel development it is obstructed by the two electrodes comparative with the case for laser ignition where the flame has a spherical form due to the fact that it doesn't encounter any obstacle. Furthermore, the cross-section area of the flame kernel generated by the laser is larger than the one generated by the spark plug for the same time range. This happens due to the absence of quenching effect generated by the electrodes.

A third lobe of the flame kernel was generated in the case of ignition by laser, as shown in Fig. 3. Appearance and development of this lobe leads to an increased surface area at the plasma boundary, which could inhibit development of the propagating flame. This phenomenon makes the laser ignition less effective for ignition mixture close to the lean limit of  $\sim 6.5\%$  methane [17].

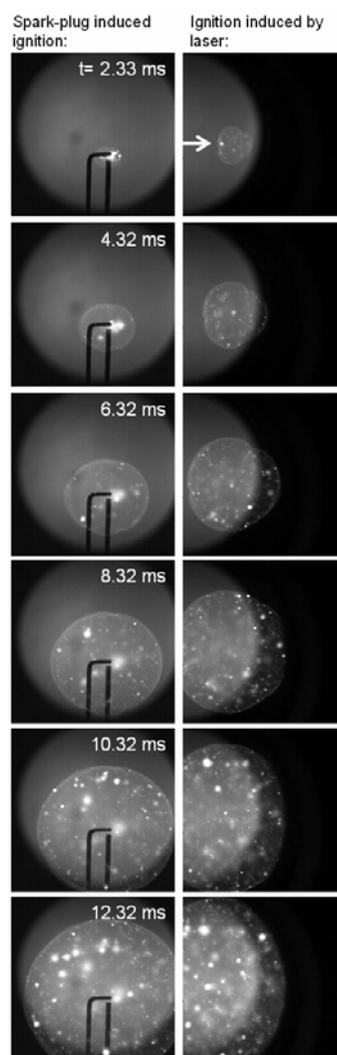


Fig. 2. Photographs of ignition induced by a spark plug and by the laser;  $t$  is the recording time from the moment when ignition starts. Filling pressure was 0.101 MPa and laser pulse energy was 22.8 mJ. The Arrow indicates the direction of propagation for the laser beam.

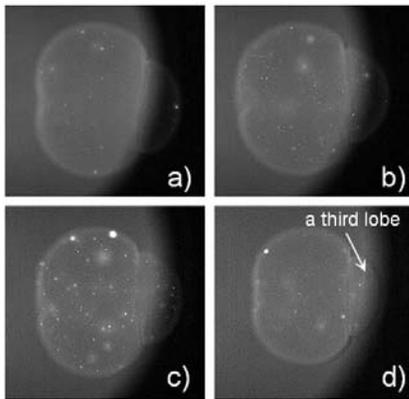


Fig. 3. Photos of laser ignition and various pressures in the combustion chamber: a) 0.1 MPa; b) 0.2 MPa; c) 0.3 MPa; d) 0.5 MPa.

Fig. 4 presents the peak pressure developed during ignition of the methane-air mixture at various values of the initial filling pressures. Increasing of the methane-air mass improves the peak pressures. On the other hand, the peak pressure generated during spark plug ignition was by 10 to 20% higher than that reached during ignition by laser. For example, when the combustion chamber was filled to a pressure of 0.101 MPa (1 atm), the peak power developed during ignition by the spark plug was 1.49 MPa, but it reached 1.21 MPa for the laser ignition process. When the filling pressure was increased at 0.506 MPa (5 atm), the peak pressure increased at 3.66 MPa for the ignition by the spark plug, and at 3.33 MPa for the laser ignition process. This behavior is supposed to come from much higher energy delivered by the electric spark compared with laser pulse, allowing the flame front to develop faster.

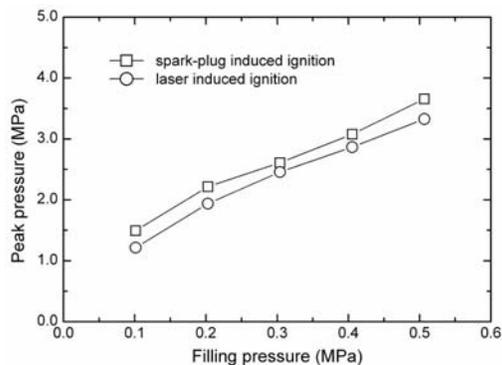


Fig. 4. Peak pressure versus the filling pressure for ignition by a spark plug and by the Nd:YAG laser is shown.

Previous investigations on methane-air mixtures [2, 18] concluded that higher peak pressures can be reached with more energetic laser pulses. This would be very interesting for engine applications because increased peak pressures means improved efficiency. We have observed only a small decrease (by up to 10%) of the peak pressure when laser pulse energy was decreased up to 12.8 mJ (the minimal energy that assured laser ignition). Therefore, in

our experimental conditions, the peak pressure depended weakly of the laser pulse energy above the 100% ignition threshold. On the other hand, calculus shows that the laser intensity that is sufficient to ignite the methane/air mixture was about  $10^{11}$  W/cm<sup>2</sup>.

The time necessary for the pressure inside the combustion chamber to rise from 10% pressure peak value to its maximum value was determined from measurements of pressure history taken with the pressure transducer. Results are shown in Fig. 5a. Generally, the building time increased when the filling pressure was higher. In the case of ignition by the spark plug, the time rise from 23.3 ms for a filling pressure of 0.101 MPa (1 atm) to 28.7 ms for the maximum filling pressure of 0.506 MPa (5 atm). The time was longer, by ~10%, in the case of ignition obtained by laser compared with classical ignition by a spark plug. Fig. 5b shows the flame speed versus initial filling pressure. One could easily observe that the speed of the flame generated by laser ignition is faster than that of a flame initiated by spark plug. This behavior can be related with turbulent motion of the hot core gas induced by the ignition laser plasma and by influence of spark plug electrodes.

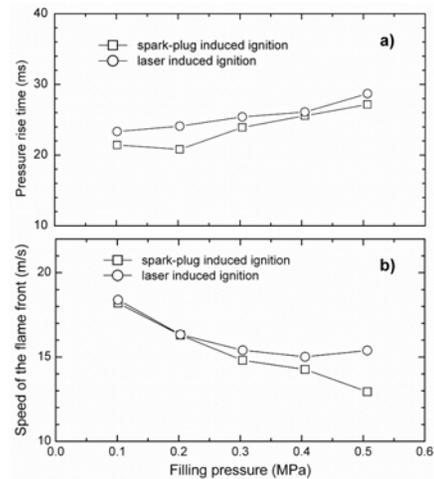


Fig. 5. a) Time for the pressure to increase from 10% value of its peak to its maximum value. b) The propagation speed of the flame versus initial filling pressure. The laser pulse energy was 22.8 mJ.

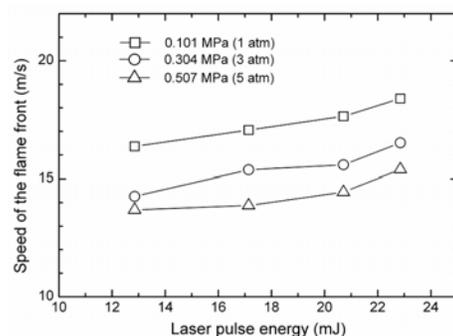


Fig. 6. Flame speed versus energy of the laser pulse used for ignition, at various values of the initial filling pressure.

Finally, the speed of the flame front obtained when ignition was realized by the laser was determined as function of the laser pulse energy, and at different initial pressures inside the combustion chamber. Fig. 6 presents the results. Rising the laser pulse energy increased slightly the flame front speed. For example, at 0.101 MPa initial pressure' filling, the flame front speed was 16.4 m/s for a laser pulse energy of 12.8 mJ. This speed increased at 18.4 m/s when the available laser pulse energy of 22.8 mJ was used for ignition. On the other hand, an increase of the initial pressure decreased the flame front speed. Thus, filling the combustion chamber with methane/air mixture at 0.507 MPa (5 atm) reduced the flame front speed at 15.4 m/s, for a laser pulse with energy of 22.8 mJ.

#### 4. Conclusions

A comparative investigation of ignition obtained by classical electrical spark plug and by an electro-optical Q-switched Nd:YAG laser in 12% methane-air mixture was performed. The shadowgraph method was used to investigate the early stages of the ignition process. Various parameters of the ignition, such as the peak pressure, the pressure building time, or the speed propagation of the flame front were analyzed at various initial filling pressure of the combustion chamber, or function of the laser pulse energy. The flame kernel development generated by laser ignition has a spherical form and its cross-section area is greater in comparison with the spark plug igniter. The peak pressure increases when initial filling pressure is raised, but a lower peak pressure was developed for the ignition by the laser. The flame front speed is faster when more energetic pulse is used to initiate the ignition at constant filling pressure. Increasing the initial filling pressure in the combustion chamber lowers the flame front speed at constant laser pulse energy. These are preliminary results in our attempt to realize and demonstrate laser ignition by a miniature, passively Q-switched Nd:YAG/Cr<sup>4+</sup>:YAG laser [19].

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