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Application of laser ignition to hydrogen–air mixtures at high pressures

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Abstract

To optimise combustion in a wide field of applications, lasers represent attractive future alternative ignition sources, especially for internal combustion engines. Experiments were carried out in a high pressure, constant volume chamber (up to 25 MPa peak pressure and initial temperature of 473 K). Laser induced ignition of different hydrogen–air mixtures (air/fuel equivalence ratio $\lambda = 1.8$–8) was investigated, using different filling pressures ($p = 0.5$–4.2 MPa), different ignition energies (pulse energy $PE = 1$–50 mJ), different chamber temperatures ($T = 393$–473 K) and different focal length lenses ($f = 60$, 120 mm). A Q-switched Nd:YAG laser at 1064 nm with a pulse duration of about 5 ns was used for ignition. An InGaAs photodetector (800–1800 nm) and a piezoelectric pressure transducer were used to characterise the combustion. Gas mixtures between $\lambda = 2.5$ and 3.6 showed knocking combustions. With increasing initial pressures the minimum pulse energy was decreasing.

Keywords: Laser ignition; Hydrogen; Lean combustion; High pressures; Laser induced plasma

1. Introduction

In recent years, interest in laser-induced spark ignition has increased because of its many potential benefits over the conventional spark plug combustion initiation. Especially for distributed generation of electric energy with high power stationary gas engines, laser ignition is of a very high interest. In these engines high load/ignition pressures are used which lead to expensive spark plugs with limited lifetimes.

Predominantly gas engines are powered by methane or other hydrocarbon based gases (biogas, gasification gas, etc.). But the today's interest is focused on alternative and special combustion gases causing low CO_2, NO_x and SO_2 emissions because of increasing public over the environment and climate change. And here hydrogen as an alternative fuel could represent a very good solution with neither CO_2 nor SO_2 emissions. In this paper the advantages of hydrogen combustion and laser ignition are combined.

Following the main advantages of laser ignition:

- a choice of arbitrary positioning of the ignition plasma in the combustion cylinder,
- absence of quenching effects by the spark plug electrodes,
- ignition of leaner mixtures than with the spark plug [1] $\Rightarrow$ lower combustion temperatures $\Rightarrow$ less NO_x emissions [1,2],
- no erosion effects as in the case of the spark plugs and lifetime of a laser ignition system is expected to be significantly longer than that of a spark plug,
- high load/ignition pressures are possible $\Rightarrow$ increase in efficiency,
- precise ignition timing possible,

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- exact regulation of the ignition energy deposited in the ignition plasma,
- easier possibility of multipoint ignition [3–5],
- shorter ignition delay time and shorter combustion time [6–8].

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 performance demand 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 efforts. A diode pumped laser ignition system has potential lifetimes up to 10,000 h compared to spark plug lifetimes in the order of 1000 h. The effectiveness of a diode pumped laser is about 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 time [3].

The experimental literature devoted to laser ignition of gas mixtures so far has stressed the low-pressure and low-temperature regimes. This publication extends the existing findings for hydrogen–air mixtures at initial pressures up to 4 MPa and initial temperatures of 473 K. Gas engines usually operate at these parameters.

In published experiments the laser spark is produced by non-resonant breakdown as mentioned in Refs. [9–11]. By focusing a (pulsed) laser to a sufficiently small spot size, the laser beam creates high intensities and high electric fields in the focal region, resulting in a well localised plasma with temperatures in the order of 10^6 K and pressures in the order of 10^2 MPa [10,12].

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 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 (dust-, aerosols- and soot-particles) [13] 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 ionisation (MPI), no wavelength dependence is expected for this initiation effect [11]. It is very unlikely that the first free electrons are produced by multiphoton ionisation because the intensities in the focus (10^{10} W/mm^2) are too low to ionise gas molecules via this process, which requires intensities of more than 10^{12} W/mm^2 [12,14].

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

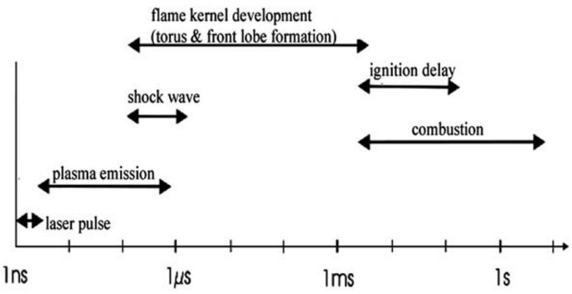

Fig. 1. Scope of timescales of various processes involved in laser induced ignition. The lengths of the double arrowed lines indicate the duration ranges of the indicated processes.

hundreds of milliseconds. The laser energy is deposited in a few nanoseconds which leads to a shock wave generation. In the first milliseconds an ignition delay can be observed which has a duration between 5–100 ms depending on the mixture. It can last between 100 ms up to 200 ms again depending on the gas mixture, initial pressure, pulse energy, plasma size, position of the plasma in the combustion chamber and initial temperature.

Many of the potential benefits and applications of the laser ignition were reviewed by Ronney [9], and a comparison of conventional and alternative ignition systems is given in Ref. [15]. Most laser ignition experiments have been carried out with methane–air mixtures [1,3,4,6–8,10,11,16–19] and fewer with hydrogen air mixtures [5,20–23].

In a number of Refs. [6,10,11,14,24–27] it is shown that the minimum pulse energy for ignition (MPE) decreases drastically with the initial pressure. This strong pressure dependence of the MPE is clearly incompatible with the multiphoton ionisation process, which predicts a very weak pressure dependence for the threshold electric field. In addition, several references [10,11,17,24–26] show an increase of the MPE towards the lean and the rich side of the stoichiometry. In Refs. [7,11] it was observed that 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. Moreover [5,11] show that with higher laser energies than the MPE, ignition delay can be shortened, and [6–8] report that laser ignition has a shorter ignition delay and a reduced total combustion time than the conventional spark ignition. Ma et al. [8] found that the flame velocity in laser ignited gas mixtures is faster than that in conventional ignited mixtures. These facts are very important for engine applications. Moreover, Beduneau et al. [17] showed that, if a longer focal length is used, (corresponding to larger plasma sizes) the MPE is increased considerably. Ronney et al. [26] showed that there is no advantage in using pico-second pulses instead of nano second pulses.

MPE (minimum pulse energy) has to be discerned from MIE (minimum ignition energy); whereas MIE is exactly