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A comparative study of laser ignition and spark ignition with gasoline–air mixtures

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The ignition probability and minimum ignition energy (MIE) of premixed gasoline–air mixture for different equivalence ratio was experimentally studied using a nanosecond pulse at 532 nm and 1064 nm from a Q-switched Nd:YAG laser in a constant-volume combustion chamber (CVCC) The result was compared with the spark ignition. The initial pressure and temperature of the mixture was 0.1 MP and 363 K, respectively. The research indicates that within the flammable range, the probability increases when the ignition energy increases and the distribution of MIE with the equivalence ratios is U-shape for both laser and spark ignition. For laser ignition with 532 nm, when the incident energy is higher than 110 mJ or the absorbed energy is high than 31 mJ, 100% of ignition could be obtained within equivalence ratios of 0.8–1.6. For 1064 nm it is 235 mJ and 30 mJ. To get the same ignition probability of mixture with identical equivalence ratio, the incident energy of 1064 nm is twice more than the incident energy of 532 nm, while the absorbed energy values are virtually the same. It indicates that significant wavelength dependence is expected for the initial free electrons but irrelevant for the process of absorbing energy. The initial free electrons are produced from impurities in gasoline–air mixture because the intensity in the focus (10^{12} W/cm^2) is too low to ionize gas molecules via the multi-photon ionization process, which requires higher irradiance ($\geq 10^{14}$ W/cm^2). The MIE obtained with a laser-spark ignition is greater than that measured by electrical sparks. The MIE for laser ignition was obtained at equivalence ratio of 1.0 both of 532 nm and 1064 nm, and it was 13.5 mJ and 9.5 mJ, respectively. But for spark ignition, the MIE is 3.76 mJ with equivalence ratio of 1.6. What's more, laser ignition extends the lean flammability limit from 0.8 to 0.6.

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1. Introduction

With the development of industry and economy, energy shortage and environmental problems have been becoming more and more serious. The internal combustion engine and automotive industry are confronted with severe and realistic challenges. Lean burn is one of the effective methods to solve the above-mentioned problems. However, current engines cannot be operated sufficiently lean due to ignition related problems such as the sluggish flame initiation and propagation along with potential misfiring [1]. It is anticipated that the spark ignition engine of the future will operate with much higher compression ratios, faster compression rates, and much leaner fuel-to-air ratios, which will aggravate the electrode degradation and erosion [2].

In order to improve the ignition stability and reduce the cycle-by-cycle variations, researchers are exploring new techniques, including plasma jet igniters [3], laser induced spark ignition [4] and rail-plugs ignition [5]. Most of the problems listed above could potentially be solved by the use of laser induced spark ignition because it has many potential benefits. The major benefits are greater control over the timing and locations of ignition. Moreover, it is accomplished without electrodes, which allows the lifetime of a laser-ignition system to be significantly longer. What is more, laser induced spark ignition would also allow ignition in multiple locations inside the chamber to shorten the combustion time of lean mixtures.

In recent years, laser ignition has become an active research topic because of its many potential benefits over the conventional electric spark ignition. Laser ignition of reactive mixtures can be divided into four categories: laser thermal ignition, laser induced photochemical ignition, laser-induced resonant breakdown ignition and laser induced spark ignition [6]. Laser induced spark ignition begins with the initial seed electrons produced from impurities in the gas mixture (e. g dust, aerosol or soot particles). It is very unlikely that the initial electrons are produced by multiphoton ionization because the intensities in the focus (10^{12} W/cm^2) are too low to ionize gas molecules via this process, which requires intensities of more than 10^{14} W/cm^2 [7,8]. Kopecek

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et al. [7] maintained that no wavelength dependence was expected for this initiation effect while Dhananjay et al. [8] hold the opposite idea that significant wavelength dependence was expected for this initiation effect based on Drude model. Initial electrons readily absorb more photons via the inverse bremsstrahlung process to increase their kinetic energy. If the electrons gain sufficient energy, they can collide with other molecules and ionize them, leading to an electron avalanche, and breakdown the gas. This process is repeated until the spark plasma of high temperature and high pressure is created. This extreme condition relative to the ambient gas leads to the development of a rapidly expanding shock wave that is of sufficient strength to ignite flammable mixtures [6].

The laser induced spark ignition has previously been found to be associated with the laser pulse width, laser energy, the size of focusing spot, the composition of mixture and its initial conditions. Studies have mainly focused on mixtures containing hydrogen [9], methane [7,10] or propane [11] although some studies have also been performed on hydrocarbon fuels such as dodecane, isooctane or Jet-A [11–13]. In these studies, the ignition characteristics are usually expressed according to the energy delivered by laser. Dhananjay et al. [8] studied characterisation of laser ignition in hydrogen–air mixtures in a combustion bomb at initial pressure of 3 MPa and temperature 323 K and the results are compared with the laser ignition ones. They found that the rate of pressure rise inside the combustion chamber was higher when the mixture was ignited by laser plasma compared with spark plug ignition. Weinrotter et al. [9] investigated laser ignition to hydrogen–air mixtures at high pressures and their results showed that with increasing initial pressures the minimum pulse energy was decreasing. Measurements and model calculations of ignition by electrical sparks and nonresonant laser sparks show that the minimum ignition energy (MIE) for laser sparks is higher than for electrical sparks [10,11,14]. Donald [14] attributed it to the higher energy cost of laser spark formation (both breakdown and heating) and more efficient removal of the energy absorbed in laser sparks to regions outside the nominal ignition kernel by the shock. Ternel et al. [12] found that a too small spark size or spark energy might result in ignition failure if the spark size is not large enough to support the flame growth or the deposited energy is less than the minimum ignition energy. Lawes [13] found that the minimum ignition energy depended on the likelihood of a droplet existing at the focus of the laser beam.

As far as we know, few papers were devoted to liquid fuel with laser induced spark ignition and there is controversy about whether the wavelength plays a role in laser ignition. This paper focuses on the impact of the equivalence ratio (Φ) and wavelength (λ) on the ignition energy [7,8]. We use a parametric study to examine the effects of the equivalence ratio and wavelength on the ignition energy values of gasoline–air mixture and results are compared with the spark ignition ones.

2. Experimental setup and experiments

Fig. 1 shows a schematic of the experimental apparatus for laser ignition, which can be separated into five main parts: ignition laser, combustion chamber, temperature and pressure measuring system, heating system and intake and exhaust system.

The optical scheme of the igniting beam is depicted in Fig. 1a, A Q-switched Nd:YAG (Dawa-100) was used as the ignition source operating at 532 nm and 1064 nm with pulse duration of 6.6 ns and 7.9 ns, respectively. The initial diameter of laser beam was 6.0 mm. After being broadened and collimated, the laser beam was focused on the center of the combustion chamber by a 500-mm focal length lens. The operating frequency range of laser is 1–20 Hz and has the single-shot mode.

The energy was controlled by the operating voltage. Two energy meters were used to measure the beam energy before and after the chamber as shown in Fig. 1a. The energy meter Ea (COHERENT J-25-MB-LE) obtained energy before the chamber by using a beam-splitter that reflected a fraction of the incident energy (2.4%@532 nm &2.0%@1064 nm) while transmitting the rest measured by the energy meter Eb(COHERENT J-50-MB-YAG). Laser energy power meter (EMP2000) could record the incident energy and transmitting energy simultaneously.

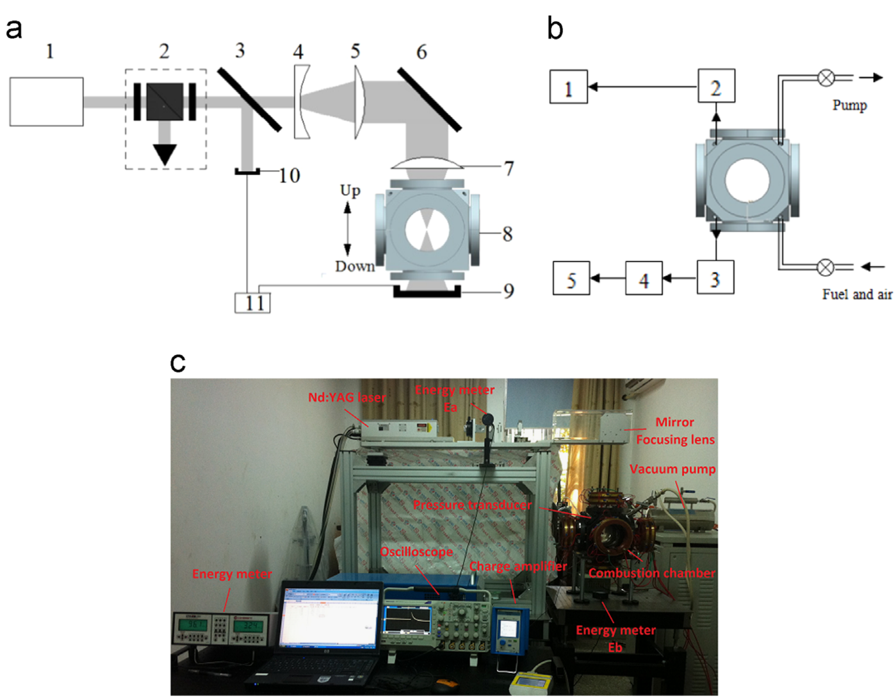

Fig. 1. Schematic of laser-induced ignition experimental apparatus. (a) laser beam propagation in the laser-induced ignition experiment, (b) top view of the constant-volume combustion chamber, (c) photograph of the experimental apparatus for laser-induced ignition.

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