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Laser-induced breakdown ignition in a gas fed two-stroke engine

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Laser-induced breakdown ignition in a gas fed two-stroke engine

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Abstract. Laser-induced ignition for internal combustion engines is investigated intensively after demonstration of a compact 'laser plug' possibility. Laser spark benefits as compared to traditional spark plugs are higher compression rate, and possibility of almost any fuel ignition, so lean mixtures burning with lower temperatures could reduce harmful exhausts (NO_x, CH, etc). No need in electrode and possibility for multi-point, linear or circular ignition can make combustion even more effective. Laser induced combustion wave appears faster and is more stable in time, than electric one, so can be used for ramjets, chemical thrusters, and gas turbines. To the best of our knowledge, we have performed laser spark ignition of a gas fed two-stroke engine for the first time. Combustion temperature and pressure, exhaust composition, ignition timing were investigated at laser and compared to a regular electric spark ignition in a two-stroke model engine. Presented results show possibility for improvement of two-stroke engines performance, in terms of rotation rate increase and NO_x emission reduction. Such compact engines using locally mined fuel could be highly demanded in remote Arctic areas.

1. Introduction

Laser ignition takes place due to gas optical breakdown followed by plasma and shock wave formation, those lead to deflagration core onset (detonation and autocatalytic reaction are also possible) [1]. Laser breakdown threshold (unlike electric) in gases decreases with pressure increase up to 10s of MPa [2], so smaller ignition energy is needed at higher compression [3]. The latter is helpful for more compact and efficient internal combustion engines (ICE) design [4]. The other benefit of laser spark plugs is possibility of lean mixtures ignition resulting in lower combustion temperatures, and therefore, reduction of harmful exhausts and thermal loads on construction [5]. Laser ignition could also be efficient for heterogeneous [6] and vortical [7] flows.

Laser ignition have been studied using different lasers (lab-class Nd:YAG, DPSS, fiber) for gasoline, hydrogen and methane based fuel mixtures [8]. However, of piston engines, we have found data regarding 4-stroke ones only [9]. Considering miniaturization, laser ignition appears rather promising for two-stroke and rotary (Wankel) engines [10]. For the latter laser ignition was only suggested by Mazda [11], and the former, to the best of our knowledge, have not been considered yet. Two-stroke engines higher volume and mass specific power, lower price and weight, and comparatively easy handing are now outweighed by higher fuel consumption rate and harmful emissions. Also, combustion is to be induced at every rotation unlike 4-srokes, this increases thermal load and results in need for more endurant ignition system. These shortcomings could be reduced at lean gas based mixtures combustion. Use of compressed

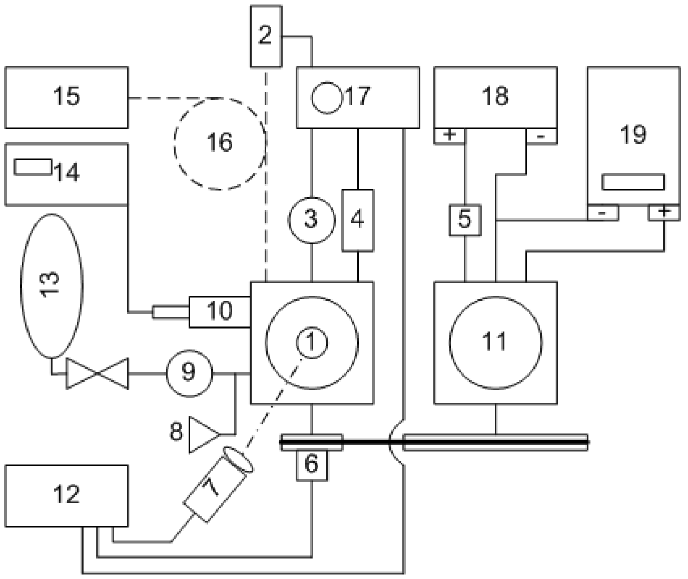


Figure 1. Experimental setup: 1—engine; 2—photomultiplying tube; 3—pressure sensor; 4—temperature sensor; 5—regulation relay; 6—rotation sensor; 7—laser; 8—drop oilier; 9—flow rate sensor; 10—silencer; 11—dc generator; 12—synchropulse generator; 13—gas bottle; 14—gas analyser; 15—spectrometer; 16—optical fiber; 17—oscilloscope; 18—accumulator; 19—electronic load.

natural gas (CNG) and liquefied petroleum gas (LPG) decrease operating costs of ICE by a factor of ca. 2. In remote Arctic areas, where gas is available from the ground, but gasoline and diesel to be brought from industrial centers, this factor can reach 10. So the aim of this work was proof of a concept and experimental evaluation of main parameters (cylinder pressure, combustion temperature, exhaust composition) of a laser ignited gas fed two-stroke engine.

2. Experimental layout

The experimental setup (figure 1) consists of GT33 (O.S. Engine) two-stroke airplane model engine (bore 36.0 mm, stroke 32.4 mm, displacement 32.98 cc) with a custom-built head that allows attachment of pressure (ADZ-SIML-20.0, Sensortechnics) and temperature sensors at the edge of combustion chamber, optical fiber for flame emission temporal and spectral analysis (SC-125, Solar LS), laser spark plug or sapphire window for ignition radiation supply, and water cooling. To load engine, automotive generator (100 A) coupled to an electronic load (ATH-8036, Aktakom) has been used. Exhaust was supplied to an industrial 5-gases (O_2, CO, CO_2, NO_x, CH) analyzer (Autotest 02.03P, Meta). Fuel tested was isobutane-propane (80:20, LPG), ignition possibility has been checked in a broad range of air/fuel ratios. Drop castor oilier was connected after carburettor for piston lubrication. Laser pulses (LS-2149 DPSS, Lotis TII—1064 nm, 12 ns, 30 mJ) were synchronized (DG645, Stanford research systems) to top dead centre (TDC) for up to 100 Hz, laser spot was focused cca 1 mm from cylinder head. Digital oscilloscope (ADS-3114, Aktakom) was used to record the signals. All timing angles are shown before TDC.

3. Results and discussion

We used the most common techniques for ICE studies. The characteristic raw data are presented at figure 2. Oscilloscope has been synchronized to TDC (Hall rotation sensor meander width equals to 27°). Combustion brightness temperature was evaluated by Wien displacement law from IR emission spectra to be up to 2600 K that corresponds well to the published data. An example of optical emission spectrum is presented at figure 3. Combustion completeness was controlled by CH and O_2 residuals in exhaust. NO_x concentration of 16 ppm was measured for stoichiometric mixture, that was much lower than in similar sized two-strokes (cca 400 ppm [12]) and lower than in traditional four-stroke automotive engines idling (cca 25 ppm for CNG,

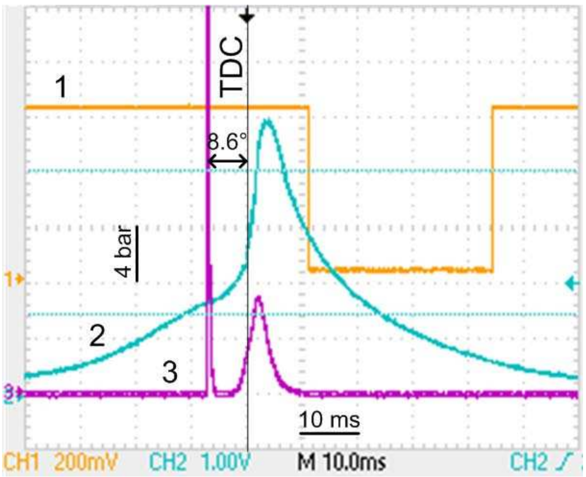


Figure 2. Typical oscillogram at 2.2 Hz: 1—rotation encoder; 2—pressure sensor (0.25 V/bar); 3—radiation sensor.

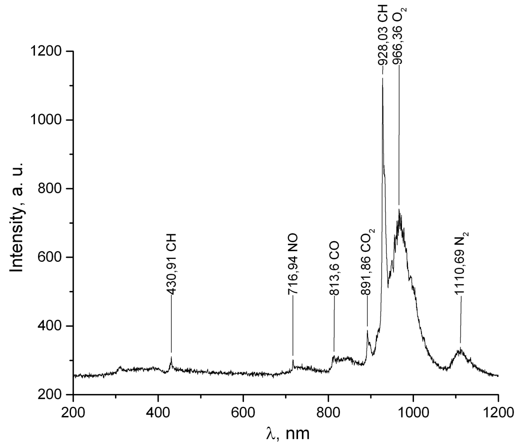
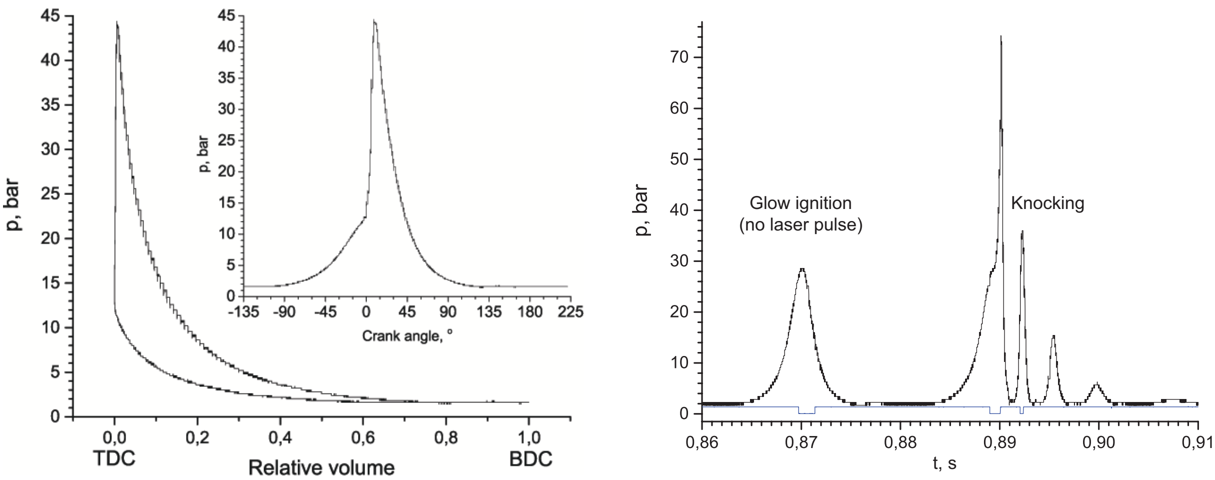


Figure 3. Time integrated spectrograph.



(*a*) (*b*)

Figure 4. (*a*) The indicator (*p*–*V*) diagram and (*a, b*) pressure dynamics at (*a*) laser-induced deflagration (CRR 41 Hz), (*b*) glow ignition and knocking (CRR 52 Hz).

50 ppm for diesel, and 100 ppm for gasoline). Soot deposits on laser spark plug protective sapphire window were ablated at beam path.

In pressure diagrams (figure 4), we could observe three regimes of engine operation: deflagration, knocking, and autocatalytic combustion (analogous to glow plug engines). We found that for laser ignition timing should be decreased as compared to traditional one, since flame core onset happens faster, this also leads to faster pressure increase. For example, at 67 Hz crank rotation rate (CRR), optimal timing for deflagration regime was 27° (compared to 42° for the same regime with gasoline electric ignition). Timing limits two-stroke maximum rotation rate because of intake window position, so with laser ignition this problem could be partially resolved. Peak pressure reached 44.4 bar (compression was up to 16 bar). Indicated horsepower was cca 15% greater than specified in the engine datasheet for gasoline (the latter could be just a guaranteed minimum though) unlike 7–15% power decrease in CNG fed 4-stroke engines with electric spark ignition. At glow ignition pressure reached 28.5 bar and at knocking—73 bar, see figure 4(*b*). It is worth mentioning, that high pressure could not be properly measured by used sensor due to its saturation at 80 bar and 1 ms temporal resolution.

Even though optical breakdown of the mixture was observed every time, it was not always ignited. Minimum ignition energy (MIE) is known to be strongly dependent on air-to-fuel ratio and pressure, the same we observed in our experiments. MIE found for engine operation with stoichiometric mixture supplied was 2.5 mJ, that corresponds to pressure of 8 bar. Such energy level can be easily reached in electric spark-plug sized diode-pumped solid state (DPSS) laser, pumped by sub-100 W cheap laser diode.

4. Conclusions

Laser ignition system allows using multiple fuels in lean mixtures at higher compression rates, so it can be used for high performance engines, e.g., for UAV, electric transport, and for harmful emissions reduction from industrial power plants. Our experiments have demonstrated for the first time the possibility of laser ignition in a two-stroke engine (with no special modification) fed by LPG (the fuel available at many locations nowadays). We have found, that such important operation parameters as timing at high rotation rate, indicated power and harmful emission in our model engine were better than those declared for its usual configuration with electric spark ignition and gasoline fueling. Significant reduction of NO_x concentration in exhaust down to 16 ppm resolves one of the main problems for two-stroke engines development—matching international emission standards. MIE of 2.5 mJ allows using compact DPSS lasers for development of laser spark plugs for LPG fed engines.

Acknowledgments

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