Laser ignition of liquid petroleum gas at elevated pressures

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Abstract. Recent development of laser spark plugs for internal combustion engines have shown lack of data on laser ignition of fuel mixtures at multi-bar pressures needed for laser pulse energy and focusing optimisation. Methane and hydrogen based mixtures are comparatively well investigated, but propane and butane based ones (LPG), which are widely used in vehicles, are still almost unstudied. Optical breakdown thresholds in gases decrease with pressure increase up to ca. 100 bar, but breakdown is not a sufficient condition for combustion ignition. So minimum ignition energy (MIE) becomes more important for combustion core onset, and its dependency on mixture composition and pressure has several important features. For example, unlike breakdown threshold, is poorly dependent on laser pulse length, at least in pico- and microsecond range. We have defined experimentally the dependencies of minimum picosecond laser pulse energies (MIE related value) needed for ignition of LPG based mixtures of 1.0 to 1.6 equivalence ratios and pressure of 1.0 to 3.5 bar. In addition to expected values decrease, low-energy flammability range broadening has been found at pressure increase. Laser ignition of LPG in Wankel rotary engine is reported for the first time.

1. Introduction
Laser-induced ignition of natural gas applied to internal combustion engines is investigated for a long time. Demonstration of a compact 'laser plug' [1] accelerated research in this field, and particularly, led to a dedicated annual international Laser Ignition Conference appeared. 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 (NOx, 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. Need in gas fed engines in general arises not from lower operating costs and harmful emissions only, but from gas direct availability in many remote regions (e.g. Arctic ones), where cost of petrol and diesel delivery is higher than of the original price of product itself.

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) [2]. Laser breakdown threshold (unlike electric) in gases decreases with pressure increase up to 10s of MPa [3], so smaller ignition energy is needed at higher compression [4]. The latter is helpful for more compact and efficient internal combustion engines design [5]. Lasers could be also rather efficient for heterogeneous [6] and vortical [7] flows ignition.
A lot of data have been published about laser ignition of methane (or compressed natural gas, CNG) \[4, 8, 9\] and hydrogen \[10-12\] based mixtures since those are more promising for stationary power plants. However, propane-butane (liquid petroleum gas, LPG) is more widely used in automotive industry because of significant benefits such as higher specific heat release, smaller weight and size of feeding system, longer run between fueling up. Despite this, only one paper is available on propane \[13\], and we failed to find any on butane or LPG based mixtures laser ignition.

Usually minimum ignition energy (MIE) is experimentally evaluated, and it is found to be significantly higher than for electric ignition, as explained, due to shorter duration and smaller size of the laser impact region \[14\]. MIE is strongly dependent on air-to-fuel ratio and pressure, and is virtually independent on laser pulse length, at least starting from picosecond \[15\] to microsecond range. Data available still have a lot of discrepancies, reaching an order of magnitude or even more. Those originate both from multiple experimental conditions features, such as laser focusing \[16\], gas velocity and temperature \[17\], etc., and from what the researcher assumes as the MIE: this could be the least energy in a long train of pulses, or the one that leads to a guaranteed ignition \[18\]. Another significant detail, which stays unclear very often, is weather MIE is defined as an incident or acting energy (incident minus transmitted). The objective of this work was to obtain missing data on MIE of LPG based mixtures at different pressures and to check the obtained results in a model engine.

2. Experimental layout

Single pulses of Nd:YAG laser radiation (1064 nm, 71 ps, LS-2151, Lotis TII) were focused by a 100 mm focal length fused silica lens (25.4 mm dia.). Chamber volume (consisting of standard 40 i.d. vacuum crosses) was vented and pumped down to 1 mbar prior to every measurement. Gas was fed to a partial pressure according to a desired fuel mixture composition, controlled by a membrane vacuum gauge (CTR100, Ceravac). And finally, air was supplied by compressor to the pressure controlled by gauge and a special sensor (ADZ-SIML-20.0, Sensortechnics). To characterize mixture composition we normalized it to 30.5 oxidizer/fuel volumetric (and partial pressure) ratio as stoichiometric \( r_{\text{stoich}} \) for 6% propane, 30% butane, 64% isobutane (commercial bottle for gas burners). So equivalence ratio was calculated as \( \phi = r_{\text{stoich}} / r \). Control photodiode was calibrated with energy meter (30A-P-RP, Ophir) placed instead of the target before each measurement series following a usual procedure. Safety valve opening at 4 bar limited the upper pressure range. Optical breakdown was identified by plasma radiation using a fiber coupled photo multiplying tube (H6780-04, Hamamatsu), which was blind to incident laser radiation.
3. Results and their discussion

We have measured incident MIE, or minimum pulse energy (MPE) as a more practical one, for mixtures of 0.6 to 1.6 equivalence ratio at initial pressure 1 to 3.5 bar, at room temperature. Our laser was unable to supply enough energy for ignition of mixtures with φ less than unity, but it was always far enough for laser breakdown. The results are presented at figure 2. Two trends very important for laser ignition could be seen. MPE, as expected, decreases significantly with pressure increase, same as gas optical breakdown threshold does. Minimum of the dependency drifts towards greater φ (richer mixture), but at the same time curve meander broadens making ignition less sensitive to pulse energy in a wider range of equivalence ratios. Although, data confirming these features can be found in literature for other gases, nothing like this has been shown up to date since very works consider both different pressures and equivalence ratios. Figure 2b also shows that at φ>1.3 MPE dependency on pressure becomes more steep with equivalence ratio increase.

For electric ignition, MIE dependency minimum is known to move towards richer mixtures with fuel molecular weight increase [19]. This is also confirmed for laser ignition at 1 bar: for hydrogen MIE minimum was at φ~0.85 [20], for propane – at φ~1.2 [13], and for dodecane – at φ~3.7 [13]. The optical breakdown threshold was not so sensitive to the mixture composition, obtained value was 1.5 mJ at φ=1, p=1 bar.

![Figure 2. Dependency of MIE on mixture equivalence ratio (a) and pressure (b) at ps-laser impact.](image)

Data for comparison are available for methane, hydrogen and propane at φ=1 and p~1 bar mostly. For propane MIE was 0.8 mJ [13], and that is the case when the great difference comes from methods of MIE and MPE measurement. We found in our experiments that 82% of laser radiation was transmitted through the focal region at φ=1 and p=1 bar at MPE, at lower energies still sufficient for breakdown up to 98.5% was transmitted through the focal region.

The results we obtained using nanosecond laser pulses did not differ significantly from the discussed above. However, greater pulse energies available from nanosecond lasers allowed igniting mixtures in a broader range of φ and p. At mixture pressure of 8 bar, that it usual for ignition in a 2-stroke piston engine, MPE was 2.5 mJ [21]. For methane at 10 bar it is known to be 3 mJ [22]. These values are easily reachable in compact DPSS lasers making those very promising for laser spark plugs design.

We have checked our findings on MPE in a model Wankel rotary engine (49-PI, O.S. Engines) that is normally ignited by glow plug of only 6 mm dia. (type F). For that, we used specially designed laser spark plug based on passively Q-switched Cr/Nd:YAG rod with resonator mirrors coating on edges.
end-pumped with a fiber-coupled 50 W laser (FL-FCSB04-50-808, Focuslight). The radiation pulses of 2.5 mJ were focused by 6 mm dia. half-ball lens. Ignition timing was synchronized with shaft rotation. The engine was fed by a rich mixture φ~1.2 and was able to spin up to 15,000 r.p.m. without load. Since engine started deceleration immediately after radiation switch off, glow ignition did not take place.

4. Conclusions

Data on minimum laser pulse energy for butane based LPG fuel mixtures ignition at elevated pressures have been obtained for the first time. Also for the first time, we have shown that at pressure increase minimum of ignition energy dependency on air/fuel ratio drifts towards richer mixture. But at the same time, meander of this dependency becomes broader allowing low energy laser ignition in a wider range of equivalence ratios.

Regarding to LPG abundance in transportation, these data are of extreme importance for the development of laser ignited engines. For example, we have shown for the first time possibility of Wankel engine operation with LPG being laser ignited. This can significantly reduce operating costs and harmful emissions for this very compact type of engines.

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