Comparison of laser breakdown and laser ablation ignition thresholds of combustible gas mixtures

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Abstract. One of the strong advantages stated for laser spark plugs is the ability to ignite fuel lean mixtures resulting in improved fuel economy and reduced NO\textsubscript{x} emission. However, lean mixtures demand high laser pulse energies for ignition. That could be overcome by using laser ablation rather than optical breakdown plasma to establish the combustion core. For fuel equivalence ratios $\phi \approx 0.4\text{–}1.3$, we have experimentally compared ignition thresholds for these two cases at pressures of $p \approx 1\text{–}3$ bar of a butane-based combustible mixture. Our results show that laser pulse energy for fuel lean mixtures ignition can be significantly (by more than an order of magnitude) reduced using the ablator (stainless steel SS304) as compared to optical breakdown.

1. Introduction
Laser ignition of fuel mixtures is now thoroughly studied for reciprocating [1,2], rotary, and jet [3] engines as a substitution for traditional ignition systems providing higher reliability, broadening operation pressure range, available to ignite fuel lean mixtures with the relevant decrease in fuel consumption and harmful emissions [1].

Laser spark plug size and cost depend significantly on the output pulse energy, so the most efficient use of the latter is desired [2, 4]. This can be implemented in laser ablation ignition [5, 6], where laser beam is focused on solid target surface (unlike in gas breakdown ignition) to generate plasma. Usually, ablation plasma threshold for solids is at least one order of magnitude smaller than for surrounding gas optical breakdown. Such drop in required ignition energy can significantly reduce the size and the cost of laser ignition system. However, combustion core spoiling by the ablator and lifetime of the latter are important issues to consider.

Minimum ignition energies (MIEs) of fuel mixtures have been studied over a broad range of conditions [7–9]. Laser ablation thresholds values have been also studied widely [10, 11]. Those appeared to be much harder to evaluate numerically than MIE, being more dependent on target surface, structure and thickness [12], than on pulse and wavelength. So a lot of experiments have been conducted to obtain reliable data. However, for laser gas breakdown ignition should be also considered carefully in terms whether it is incident or absorbed value [13,14]. For practical needs, this value should be determined only experimentally for a particular engine cylinder construction, since it depends on many factors: local distribution of fuel equivalence ratios, heat losses, speed fuel components, etc. It has been shown that laser pulse energies of mJ order are sufficient to ignite hydrocarbon gas fuel mixtures [9,15,16]. Although, calculated MIE values are
Figure 1. Experimental setup: 1—combustion chamber; 2—Nd:YAG laser; 3—probing laser; 4—camera; 5—gas bottle; 6—vacuum pump; 7—valves; 8—air compressor; 9—beam expander; 10—objective; 11—membrane vacuum gauge; 12—interference filter; 13—edge; 14—lens; 15—oscilloscope; 16—energy meter; 17—beamsplitter; 18—drop-off valve; 19—ablador; 20—high pressure sensor.

much lower since a significant part of energy is not absorbed by gas, so just wasted [14,17]. For laser ablation ignition, i.e., ignition of fuel mixtures by laser-induced plasma from solid targets, these losses can be significantly reduced.

Inasmuch as almost no comparable data on gas breakdown and ablation ignition thresholds are published (except [5]), we have performed an experimental investigation of minimum laser pulse energies at optical breakdown ignition and laser ablation ignition with stainless steel SS304 ablator, fuel mixture (butane based) compositions (fuel equivalence ratios $\phi \approx 0.5–1.3$) and pressures ($p \approx 1–3$ bar).

2. Experimental setup

Our experimental setup is shown in figure 1; both the setup and the experimental procedure have been described in details elsewhere [14]. Nd:YAG laser (Solar LS LQ929) was used for impact (1064 nm, 12 ns). Gas (a commercial mixture for gas burners: propane—6%, butane—28%, isobutane—60%, impurities—6%) was supplied in accordance with the required air–fuel composition. Fuel pressure, when purged into evacuated volume, was controlled by a membrane vacuum gauge (CTR100, Ceravac). Air was supplied by compressor to a pressure controlled by piezo-sensor (ADZ-SIML-20.0, Sensortechnics). Schlieren technique was used to observe the impact area using intensified ccd camera (Nanoscan Nanogate-2). Ablation and breakdown thresholds without ignition were identified by shock wave presence on the images. Ignition was obvious by many signs including flame, pressure rise, and drop-off valve opening sound. Steel rod tip matched the focal plane of the lens as identified by optical breakdown in the air.
3. Results and discussion

Minimum laser pulse energies (MPE) for breakdown ignition were experimentally evaluated by us in [13, 14]. MPE for ablation and gas breakdown are presented in figure 2. One can see in figure 2(d) a significant difference between the two means of ignition. The measured MPE for both ablation and gas breakdown is one order of magnitude higher than that reported in [5] for laser ignition of methane–oxygen mixtures. Similar difference exists to data reported in [18], where 1 mJ laser ablation ignition of oxygen–methane and kerosene–oxygen fuel mixtures was investigated. Authors stress that ignition was obtained at 100 Hz pulse repetition rate only, so some incubation effects took place. Moreover, local total pressure in the chamber could be rather different to 1 bar. In both cases, difference can be also explained by the fact that energy required to ignite a methane–oxygen mixture is much lower than for a methane–air mixture [19]; results for gas jets can be different to still volume [20]; other sort of fuel gas, focal spot size, and ablator material and geometry should be also considered.

One more difference from data [5] is ablation ignition MPE($\phi$) curve shape: in our case it has distinct meander unlike slightly inclined line in cited paper [that is more similar to our ablation plasma threshold—dataset 2 in figure 2(a)]. However, in [5], there is no optimum for breakdown ignition MPE either, which does not match the results of a number of other works (e.g., [21]) where a clear optimum could be observed for stoichiometric mixture, which is known also from electric spark ignition and predicted theoretically. Minimum ablation ignition MPE values were observed at an equivalence ratio of cca 0.7 with slight tendency to move towards leaner mixtures with pressure increase. This is opposite to gas breakdown ignition MPE having an optimum at $\phi \approx 1.1$ and tendency to move towards richer mixtures with pressure increase [13, 14].
While the reason for ablation ignition MPE increase in leaner mixtures is rather obvious, it appears rather strange for stoichiometric and rich mixtures. It has been shown in [22] that at fixed pulse energy, ablation crater volume in copper increased by 100 times with ambient gas ionization potential increase by 10 eV. Crater volume is related to the ablation threshold since specific mass flow rate depends on actual laser fluence ratio to the threshold value [23].

Butane and other hydrocarbons have lower ionization potential (10–12 eV) than air (17 eV), so in rich mixtures ablation could be suppressed. Some kind of Penning effect could be meaningful, considering stoichiometric 28.5 : 1 volumetric air–fuel ratio (for methane it is 9.66 : 1, so such kind of effect is unlikely). Spatial confinement by the ablator could also spoil the combustion core development.

Ablation plasma threshold values for $\phi = 0$ were 2.29, 2.1, and 1.8 mJ at 1, 2, and 3 bar, correspondingly. These results also need some comment since values are low as compared to other data obtained at 1 bar and are higher than ablation plasma threshold at 3 bar. This confirms to some extent our suggestion that fuel gas influences the ablation process somehow, since for $\phi \approx 0.5$–0.9 ablation plasma threshold is changing considerably with pressure increase, unlike $\phi = 0$.

Ablation ignition MPE is higher than ablation plasma thresholds, but those almost equalize at optimum. Similar results were obtained in [6]: $\phi = 1$ for methane–air mixture; the ablation plasma threshold was about 1 mJ, and the ignition energy was about 4 mJ. So energy required for the formation of ablation plasma is not sufficient for ignition, unlike in gas breakdown down to $\phi \approx 0.7$. In [5], it is also shown that ablation ignition MPE matches predicted MIE well, that means almost no laser pulse energy is wasted. Moreover, for lean mixtures, MPE was even cca 2 times lower than MIE! However, authors do not explain this difference nor provide the source of MIE data. A number of questions for further research arise from these findings.

Obviously, ablation ignition leads to target erosion. If repetitive ablation occurs at the same point, plasma properties may change with shots number increase, eventually, leading to ignition termination. Moving and refreshing the target surface could solve the problem, and this should be taken into account.

4. Conclusions

Our results show that laser pulse energy for fuel lean mixtures can be significantly reduced using the ablator, and leaner mixtures could be ignited at all. The gain of using the ablator for lean mixtures ignition can reach almost a hundred as compared to laser gas breakdown ignition at higher pressures. So laser ablation can significantly reduce energy demand for laser igniters, which could make laser ignition implementation more realistic. Even though, the experimental conditions (position of the ignition region, lens focal length, location of the focus relative to the target surface, etc) were not optimized in our experiments. By optimizing these experimental parameters, MPE could be further reduced.

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