Investigation of minimum laser ignition energies of combustible gas mixtures

Y V Anishchanka, E Y Loktionov and V D Telekh

Bauman Moscow State Technical University, 2nd Baumanskaya Str., Moscow, 105005, Russia

E-mail: stcpe@bmstu.ru

Abstract. Minimum ignition energy (MIE) values for electric spark have been calculated and experimentally evaluated long ago, but for laser ignition significantly higher values were found, as explained, due to shorter duration and smaller size of the laser impact region. The feature of electric breakdown ignition is high energy input rate in the discharge channel. For laser ignition, energy input rate depends on gas spectral absorption. So only a small part of incident laser energy may be deposited in laser spark near breakdown threshold. MIE for certain gas mixture contents and pressure is expected to be independent on the way of energy deposition. There is a mess in published data on laser ignition energies, because authors often do not state whether incident or deposited energy is mentioned. To resolve these discrepancies, minimum pulse energy (MPE) term is suggested for laser impact, and is a more practical one. Although MPE is easy to measure, its value depends a lot on experimental conditions, which are not always properly documented, to reduce this effect, we suggest to consider MPE to laser breakdown energy ratio. We have experimentally evaluated MPE for butane (C₄H₁₀) based fuel mixture of different equivalence ratios (φ~0.5-1.5) and pressures (p~1-4 bar) at the impact of 1064 nm radiation of nanosecond laser. Efficiency of laser ignition was evaluated by MPE to breakdown threshold ratio.

1. Introduction

Demonstration of a compact laser spark plug [1] accelerated research in the field of combustible gases optical ignition to evaluate optimum impact parameters. 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. Minimum ignition energy (MIE) values for electric spark have been calculated and experimentally evaluated long ago, but for laser ignition significantly higher values were found, as explained, due to shorter duration and smaller size of the laser impact region [4].

MIE is known to be strongly dependent on mixture equivalence ratio φ, pressure and lens focus length. For electric spark ignition is has been shown, that MIE dependency on φ has a pronounced minimum that moves towards richer mixture with fuel molecular weight increase [5]. This is also confirmed for laser ignition at 1 bar. For H₂ was observed at φ~0.85 [6], for C₃H₈ – at φ~1.2 [7], and for C₁₂H₂₆ – at φ~3.7 [7]. The feature of electric breakdown ignition is high energy input rate in the discharge channel. For laser ignition, energy input rate depends on gas spectral absorption. So, only a percent of incident laser energy may be deposited in laser spark near breakdown threshold. However,
at combined laser impact, significant threshold decrease can be reached [8]. It is worth mentioning, that MIE for certain gas mixture contents and pressure is expected to be independent on the way of energy deposition. MIE is strongly dependent on air-to-fuel ratio and pressure, and less dependent on laser pulse length, at least in pico- to microsecond range [9]. There is a mess in published data on laser ignition energies, because authors often do not state whether incident or deposited energy is mentioned; experimental conditions features, such as laser focusing [10], gas velocity and temperature [11] are often not described properly. Also what is assumed a threshold value (the least energy in a long train of pulses, some probability rate, or the one that leads to a guaranteed ignition [12]) is not often clear.

To resolve these discrepancies, minimum pulse energy (MPE) term is suggested for laser impact, and is a more practical one for different applications [13-15]. Although MPE is easy to measure, its value depends a lot on experimental conditions, which are not always properly documented. So the best way to compare MPE’s for different fuel mixtures is to perform experimental series at the same conditions. And this was the aim of our work.

2. Experimental setup

Minimum laser pulse energies for ignition – MPE – have been experimentally evaluated for butane based (propane – 6%, butane – 28%, isobutane – 60%, impurities – 6%) fuel mixture of different equivalence ratios (\(\phi \approx 0.5-1.5\)) and pressures (\(p \approx 1-4\) bar) at the impact of 1064 nm radiation of nanosecond (~12 ns) Nd: YAG laser (Solar LS LQ929). The equivalence ratio was calculated as [16]:

\[
\phi = \frac{1}{\lambda} \sum \left( \frac{X_{C_3H_8}}{X_{C_3H_8}} \right)_{stoich} + \sum \left( \frac{X_{air}}{X_{C_4H_{10}}} \right)_{stoich},
\]

where \(x\) depicts the volume fractions of different gases, «stoich» means the stoichiometric ratio for propane and butane (which are 24.2 and 30.8, respectively); \(X_{C_3H_8} + C_{4H_{10}}\) stands for the volume fraction of the fuel gas, \(y\) defines the propane (or butane) percentage of the fuel gas (\(C_3H_8 + C_4H_{10}\)).

Experimental setup (figure 1) was developed similar to that described in [17]. To reduce effects of soot deposition on input window, it was cleaned by several laser pulses just after combustion. MPE was evaluated for 50% ignition probability [18].

---

**Figure 1.** Experimental setup (1 – combustion chamber, 2 – Nd:YAG laser, 3 – probing laser, 4 – ICCD camera, 5 – gas bottle, 6 – vacuum pump, 7 – valves, 8 – air compressor, 9 – spectrometer, 10 – optical fiber, 11 – membrane vacuum gauge, 12 – acquisition unit, 13 – temperature controller, 14 – high pressure sensor, 15 – oscilloscope, 16 – energy meter, 17 – beam splitter, 18 – lens, 19 – optical telescope).
3. Results and discussion

We have measured MPE for laser breakdown and ignition (figure 2). We failed to find quantitative comparison of these parameters at different mixture equivalence ratios \( \phi \). MPE values for both phenomena, as expected, decrease significantly with pressure increase. MPE(\( \phi \)) ignition curve approaches its minimum around the stoichiometry but at the same time, curve meander broadens making ignition less sensitive to pulse energy in a wider range of equivalence ratios. For laser breakdown, dependency on equivalence ratio is much less pronounced. Moreover, at certain point, ignition MPE becomes smaller than that for breakdown. This junction point tends to move towards leaner mixtures with pressure increase.

![Figure 2. MPE (1) and breakdown threshold (2) dependency for butane-air mixtures on pressure (a) and stoichiometry (b).](image)

To evaluate efficiency of laser ignition we suggest using ignition to breakdown MPE ratio to make data obtained at different experimental conditions comparable. E.g., for picosecond ignition, this ratio was ca. 3 [17], albeit absolute ignition MPE values were about 2 times lower. Shorter pulses in the ps regime compared to several ns, allow reduction of MPE because less pulse energy is transmitted before plasma is created which absorbs 100% of the beam energy arriving later. In our ps experiments [17], we have found that 82% of laser radiation was transmitted through the focal region at \( \phi=1 \) and \( p=1 \) bar at ignition MPE. At breakdown threshold, this value reached 98.5%.

From the practical point, MPE allows specifying the ignition laser, MIE does not. Moreover, reliable MIE evaluation in laser experiments is rather complicated. Usually, energy transmitted through focal region is subtracted form the incident. Some authors also include laser induced shockwave energy in consideration. In that case, the residual amount of energy and MIE expectation (ca. 1% of incident energy) does not exceed laser energy meter accuracy, and radiation reflected by plasma can be also comparable to this.

Laser MIE is also known to depend strongly on lens focal length since certain combustion core volume needs to be reached [4, 19]. MPE increases proportionally to focal volume (focus length). More details about this effect can be found in [20, 21]. Data for MIE are available for CH\(_4\) (MIE @ 1064 nm: 6 mJ @ \( F\sim75 \) mm [4]; 3.5 mJ @ \( F\sim150 \) mm [22]; 1.4 mJ @ \( F\sim100 \) mm [23]), H\(_2\) and C\(_3\)H\(_8\) (MIE 0.8 mJ @ 532 nm, \( F\sim50 \) mm [7]) at \( \phi=1 \) and \( p=1 \) bar mostly.

The MPE of CH\(_4\)-air has been reported by Weinrotter et al. [16] and Tauer J et al. [19]. In both cases a pulsed Nd: YAG laser with a wavelength of 1064 with pulse duration of 5 ns was used. The focal length is 60 mm. In the first case at a temperature of \( T=473 \) K and a pressure of \( p=10 \) bar, \( \phi=0.6 \)
the minimum of MPE is 3.8 mJ. In the second case at a temperature of $T=423$ K and a pressure of $p=20$ and $p=30$ bar, $\varphi=0.6$ the minimum of MPE is 5.2 mJ and 4 mJ, respectively.

4. Conclusions

Minimum pulse energies for laser ignition and breakdown are presented for butane based combustible gas mixtures for the first time. The effect of pressure and equivalence ratio on MPE was experimentally studied and analyzed. The obtained results are of great importance for laser ignition systems development. Also for the first time, we have shown that laser ignition MPE may be lower than breakdown threshold expectation.

Acknowledgements

Research has been performed at “Beam-M” facility, following the government task by the Russian Ministry of Education and Science (No. 13.6918.2017/8.9).

References

[1] Pavel N, Tsunekane M and Taira T 2011 Opt. Express 19 9378
[2] Phuoc T X 2010 Handbook of Combustion (Weinheim, Wiley-VCH Verlag GmbH) p 95
[3] Loktionov E Y, Pasechnikov N A, Protasov Y S, Protasov Y Y and Telekh V D 2015 J. Appl. Spectrosc. 82 607
[4] Phuoc T X and White F P 1999 Combust. Flame 119 2036
[5] Lewis B and von Elbe G 1987 Combustion, Flames and Explosions of Gases. (Orlando: Academic Press)
[6] Syage J A, Fournier E W, Rianda R and Cohen R B 1988 J. Appl. Phys. 64 1499
[7] Lee T-W, Jain V and Kozola S 2001 Combust. Flame 125 1320
[8] Loktionov E Y, Pasechnikov N A and Telekh V D 2016 J. Phys.: Conf. Ser. 774 012125
[9] Ronney P D 1994 Opt. Engin. 33 510
[10] Srivastava D K, Wintner E and Agarwal A K 2014 Opt. Laser. Engin. 58 67
[11] Griffiths J, Riley M J W, Borman A, Dowding C, Kirk A and Bickerton R 2015 Opt. Laser. Engin. 66 132
[12] Xu C, Fang D, Luo Q, Ma J and Xie Y 2014 Opt. Laser Technol. 64 343
[13] Loktionov E Y, Pasechnikov N A and Telekh V D 2018 J. Phys.: Conf. Ser. 946 012066
[14] Kuzenov V V and Ryzhkov S V 2013 Probl. Atom. Sci. Technol. 103 103
[15] Kuzenov V V and Ryzhkov S V 2016 Bull. Rus. Acad. Sci.: Phys. 80 598
[16] Weinaroter M, Kopecek H, Tesch M, Wintner E, Lackner M, Winter F. 2005 Experim. Therm. Fluid Sci. 29 569
[17] Loktionov E, Pasechnikov N and Telekh V 2017 J. Phys.: Conf. Ser. 927 012030
[18] Mokrani N, Gillard P 2018 J. Hazard. Mat. DOI: 10.1016/j.jhazmat.2018.03.046
[19] Tauer J, Kofler H and Wintner E 2010 Laser & Photon 1 99
[20] Dharamshi K, Agarwal A K, 2014 Int. J. Hydrogen Energy 39 20207
[21] Kopecek H, Maier H, Reider G, Winter F, Wintner E 2003 Experim. Therm. Fluid Sci. 27 499
[22] Li X, Yu Y, Yu X, Liu C, Fan R, Chen D 2014 Opt. Express 22 3447
[23] Bondre S V 2004 Master's Thesis, University of Tennessee