Laser spark plug developments for engine ignition (Invited)

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Abstract: The authors outline progress made over the last years in laser ignition (LI) research, in particular that targeting laser sources (or laser spark plugs) with dimensions and properties suitable for operating directly on engines. Some of the envisaged solutions for design and implementation are introduced. The path taken, from the first approach to build a compact laser suitable for engine ignition, to the practical realization of a laser spark plug, is described. Some results obtained from LI of test engines with devices resembling classical engine spark plugs are discussed, emphasizing the technological advances which have brought LI close to application in automobile gasoline engines. Scientific and technical advances have led to the realization of laser devices with multiple beam outputs, but many other important aspects such as integration, thermal endurance and vibration resilience are still to be solved. Recent results of multi-beam LI of a single-cylinder test engine are encouraging and have led to increased research interest in this direction.

1. Introduction

Extensive research in LI has been performed in the last decades to address the limitations of electrical spark plug ignition, including poor capability to ignite lean air-fuel mixtures, limited performance at higher pressures and inflexibility of the ignition position inside the combustion chamber. Though electric spark plugs are simple and inexpensive devices, the electrodes suffer from wetting and erosion, while their protrusion into the cylinder volume can quench the emerging combustion flame kernel. Compared to electric spark ignition (SI), LI offers several potential advantages. There are no electrodes. A laser beam can be propagated and focussed into an engine cylinder by externally placed optics, creating the laser spark at any position in the combustion chamber, to optimise flame propagation distance and reduce combustion duration. LI offers the potential to deliver the energy simultaneously to different spots to realize spatial multipoint control of LI, or a sequence of laser pulses at the same spot within a very short time span, for temporal control of LI. These two last features can enable improved ignition of lean air-fuel mixtures or of high-pressure mixtures in reciprocating engines, though they are not easy to exploit. Considering these advantages, LI has been investigated in stationary gas engines for energy cogeneration, in ground-based turbines, aero turbines, rocket and scramjet engines, and in reciprocating engines. Up to now, however, there is no commercial combustion engine ignited by such a system, or at least operated with LI for a period comparable with the lifetime of SI plug. Only since 2012/13, automobiles with gasoline engines were fully run with LI by two research groups.

Here, we outline progress made in research on LI of reciprocating engines, especially of gasoline engines. A short history presents steps taken to develop a spark plug-like LI system for automobile engine applications. We then discuss approaches to beam delivery into the engine cylinder, advances in remotely pumped LI sources, multi-point and multi-event LI techniques, and some of the test engine performance results obtained with these.

2. Selected history of LI

The first demonstration of laser-induced optical breakdown in air [1] in 1962, using a frequency-tripled Q-switched ruby laser pulse, is generally considered as the starting point for research on LI. In 1969 LI of chemically reactive gaseous mixtures in a combustion chamber (or 'explosion bomb') was investigated by Lee and Knystautas [2], using a Q-switched ruby laser and saturable absorber (SA) dye cell to yield 10 ns duration pulses. The minimum ignition energy (MIE) was found to be 1.2 J. In 1971, Weinberg and Wilson [3] reported on the LI of stoichiometric methane-air mixtures in a combustion chamber with a passively Q-switched ruby laser (30 J/20 ns). Compared to SI, LI initiated shorter duration and smaller volume plasma, giving decreased MIEs and quenching distances In 1974, Hickling and Smith [4] of General Motors Corp. reported on the LI of isooctane, cyclohexane, n-heptane, n-hexane, clear indolene and diesel in a combustion bomb. They considered LI to be impractical "because of its low efficiency and high cost", yet highlighted the advantage of an 'electrode-less laser' able to target any location inside the combustion chamber.

The first demonstration of LI of an internal combustion engine was achieved by Dale et al. in 1978 [5], igniting a single-cylinder engine with CO_2 laser pulses (0.3 J/50 ns) focused through a ZnSe window to different positions inside the chamber. Compared to SI, LI gave higher peak pressure, higher engine power and reduced fuel consumption, yet emissions of CO and HC were similar and NOx emissions were higher. LI gave an extended lean limit (AFR~22.5) and improvements in engine performance by moving the laser focus away from the cylinder walls. In 1998, Ma et al. [6] studied LI of various combustible mixtures (methane-air, hydrogen-air, propane, dodecane, jet-A fuel) using both excimer and Nd:YAG lasers. LI of a single-cylinder engine with a Q-switched Nd:YAG laser (1064 nm, 160 mJ/6 ns) by Liedl et al. in 2004 [7] found LI reduced fuel consumption by several % and reduced exhaust emissions by ~20% compared to SI. In 2006, Dodd et al. demonstrated LI of one cylinder of a 4-cylinder Ford Zetec gasoline test engine, then in 2007/2008 Mullett et al. reported the first LI of a full 4-cylinder engine [8]. LI gave improved combustion stability (COV_{IMEP}) and could ignite leaner air-fuel mixtures, compared to SI.

The many studies on combustion characteristics of LI included a review and comparison of initiation processes in SI and LI, by Ronney in 1994 [9]. This found the main advantage of LI to be the free choices of laser spark position and timing, faster burning and expansion of product gases at low temperatures (minimizing NOx production). Many works on LI can be mentioned here. Fundamental aspects were reviewed by Bradley et al. in 2004 [10] and by Phuoc in 2006 [11]. Other important aspects of LI were reviewed more recently by Tauer et al. [12], Morsy [13] and Dearden et al. [14]. These identified the need for compact LI sources, robust enough to work reliably in adverse conditions of pressure, vibration and temperature and that can be installed directly on an engine, similar to SI plugs.

3. Laser spark plug development and application in engine ignition

Many afore-mentioned experiments made use of sizeable, robust, commercially available lasers typically delivering tens of mJ pulse energy with ns pulse durations. While these served the needs of research, practical LI systems would require advances in compact, spark-plug like lasers and methods to deliver the beam into the engine cylinder.

Optical fibre delivery for LI applications. This was investigated by several groups for transferring the laser pulse from the source to the engine. Fibre flexibility allows a free transfer path with less influence of vibration on optical alignment. It is also less prone to dirt and pollution and requires little space for mounting. The beam exiting the fibre end can be relatively easily focused into the combustion chamber. Several works on results obtained with coated hollow fibres, step-index silica fibres, large-clad fibres, photonic crystal fibres and Kagome fibres were described and analysed. In 2013, a review of high-power fibre delivery research for LI applications by Yalin [15] concluded that fibre beam delivery methods and the realization of combustion initiating sparks still faced numerous technical challenges. Key issues were the transmission losses due to bending and lifetime of various fibre types. Multiplexed fibres can reduce the number of lasers necessary for LI of an engine and therefore were considered of future interest.

Compact diode-pumped solid-state lasers for LI. The concept for a laser spark plug was described by Weinrotter et al. in 2005 [16], proposing one ignition laser per engine cylinder and a remotely located pump source. To avoid the need for high voltage used in electro-optical Q-switching, a passively Q-switched microchip laser was proposed with quasi-continuous wave optical pumping at low peak power by optical fibre transfer from diode lasers. The concept was demonstrated by Kofler et al. in 2007 [17] for engine ignition (6 mJ/3 ns), with a Nd:YAG laser end-pumped by diodes at 808 nm and passively Q-switched by a Cr^{4+}:YAG SA. Similar spark-plug like laser devices were developed by several other groups, with just a few highlighted here. In 2009, Kroupa et al. of Carinthian Tech Research AG in Austria developed a spark-plug like laser (HIPoLas®), based on side pumping of discrete Nd:YAG and Cr^{4+}:YAG, and reported on the use of their first prototype in a single cylinder engine [18]. Composite Nd:YAG/Cr^{4+}:YAG lasers, end-pumped by fibre-coupled diode lasers, were investigated in Japan by the Laser Research Centre, IMS, Okazaki with Nippon Soken, Nishio and in Austria at the Technical University of Vienna. The IMS team in Japan then reported on an Yb:YAG/Cr^{4+}:YAG ceramic laser in 2013 [19].

Vertical Cavity Surface Emitting Laser (VCSEL) pumped LI systems. Given the temperature sensitivity of diode laser wavelength ($\Delta\lambda_{em}$~0.3 nm/K), a 10°C change can shift the diode laser emission out of the Nd:YAG absorption spectrum (bandwidth <3 nm at 0.81 μm). A solution explored for this has been pumping with VCSEL power arrays. With five times less temperature sensitivity of its emission wavelength than a diode laser, cooling is not necessary up to ~80°C. VCSEL pumped laser igniters have been investigated by several teams and devices with 10-20 mJ pulse energies have been developed by companies Bosch GmbH in Germany, Princeton Optronics in USA and Ricoh Co. in Japan.

Multi-point LI. Variable location of ignition points in each cylinder is seen as enabling better combustion of lean air-fuel mixtures and improved engine performance. The distance a flame has to cover during combustion is shorter than in single-point ignition; hence, combustion time is reduced, less heat is lost and the higher temperatures and pressures improve efficiency and increase engine power. Early research included: using two lasers, a conical cavity arrangement to generate 2 foci, and 2-3 point LI by beam splitting. Compact lasers with multiple beam output were also realized, as additional developments to that described above. At the University of Liverpool [20], a different approach used a spatial light modulator addressed by computer generated holograms to generate multi-beam output from one Nd:YAG laser beam (532 nm; 10 ns). In single-cylinder engine tests, two 27 mJ LI points were positioned 4 mm apart in the chamber. Compared to single point LI, dual-point LI gave increased output power and more stable combustion, with less percentage of misfiring. The improvements gained were more significant for increasingly lean mixtures. All these are important results and could trigger future development of multiple-beam output lasers.

Building on these research accomplishments, a car was successfully propelled entirely by LI for the first time in Japan, as reported by Taira et al. in 2013 [21]. In 2017, the National Institute for Laser, Plasma and Radiation Physics in Romania and Renault Technologies Roumanie also succeeded in running a car, as well as a 4-cylinder engine test bench, entirely by LI [22]. In each case, compared to SI, LI improved engine stability (especially at low speed and moderate load), decreased CO and HC emissions, but increased NO_x emissions. LI of natural gas engines has been studied by, amongst others, Argonne National Laboratory (ANL) and the National Energy Technology Laboratory, USA. At ANL, a laser spark plug pumped by fibre-coupled diode laser was used to run a single-cylinder natural gas engine. A 4-cylinder natural gas stationary engine was operated entirely with laser spark plugs, built with VCSELs as pump sources. In this latter case, LI gave an increase in engine efficiency of $\sim$1.47% in comparison with SI [23].

4. Conclusions

LI offers several potential advantages of importance and interest from both research and practical viewpoints. The history and results of LI research were reviewed in outline, showing the steps taken towards putting LI into practice. Optical fibre beam delivery from a laser source placed remote to the engine cylinder was discussed but, at the time of reporting here, the results obtained from this approach are inconclusive. Though its simplicity and flexibility are attractive, the development of optical fibres of high-damage threshold remains a research challenge. Passively Q-switched laser spark plugs positioned on the engine cylinder, pumped from a remote source, seem the most attractive approach for LI of engines. Developing sources capable of operation in adverse conditions of vibration and temperature is challenging, yet several laser spark-plug igniters have now been realized. The preferred laser medium is a composite Nd:YAG/Cr^{4+}:YAG structure (single crystal or all-polycrystalline) with monolithic laser oscillator. Fiber-coupled diode lasers are the most popular pump sources, but VCSELs have also shown promise due to a lesser influence of temperature on emitting wavelength and output performance. Compact lasers with multiple-beam output were also realized, but compactness and reliable operation in adverse conditions are issues needing further attention, yet multi-point LI has shown engine performance improvements that may encourage further work on such sources.

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5. References

[1] P.D. Maker, R.W. Terhune, C.M. Savage, in 3rd Int. Conf. Quantum Elect., Paris, 1559-1572 (1963).
[2] J.H. Lee and R. Knystautas, AIAA J. **7**(2), 312-317 (1969).
[3] F.J. Weinberg and J.R. Wilson, Proc. of the Royal Society A: Mathematical, Physical and Engineering Sciences **321**(1544) 41-52 (1971).
[4] R. Hickling, and W. Smith, SAE International, Paper 740114 (1974).
[5] J.D. Dale, P.R. Smy, R.M. Clements, SAE International, Paper 780329 (1978).
[6] J. X. Ma, D.R. Alexander, D.E. Poulain, Combust. Flame **112**(4), 492-506 (1998).
[7] G. Liedl, D. Schuocker, B. Geringer, J. Graf, D. Klawatsch, H. Lenz, W. Piock, M. Jetzinger, P. Kapus, SPIE vol. 5777, 955-960 (2004).
[8] J.D. Mullett, P.B. Dickinson, A.T. Shenton, G. Dearden, K.G. Watkins, SAE Technical Paper 2008-01-0470 (2008).
[9] P.D. Ronney, Opt. Eng. **33**(2), 510-521 (1994).
[10] D. Bradley, C.G.W. Sheppard, I.M. Suardjaja, R. Woolley, Combust. Flame **138**(1-2), 55-77 (2004).
[11] T.X. Phuoc, Opt. Lasers Eng. **44**(5), 351-397 (2006).
[12] J. Tauer, H. Kofler, E. Wintner, Laser & Photon. Rev. **4**(1), 99-122 (2010).
[13] M.H. Morsy, Renewable and Sustainable Energy Reviews **16**(7), 4849-4875 (2012).
[14] G. Dearden and A.T. Shenton, Opt. Express **21**(S6), A1113-A1125 (2013).
[15] A.P. Yalin, Opt. Express **21**(S6) (2013) A1102-A1112.
[16] M. Weinrotter, H. Kopecek, E. Wintner, M. Lackner, F. Winter, Int. J. Hydrogen Energy **30**, 319-326 (2005).
[17] H. Kofler, J. Tauer, G. Tartar, K. Iskra, J. Klausner, G. Herdin, E. Wintner, Laser Phys. Lett. **4**(4), 322-327 (2007).
[18] G. Kroupa, G. Franz, E. Winkelhofer, Opt. Eng. **48**(1), 014202 (2009).
[19] M. Tsunekane and T. Taira, IEEE J. Quantum Electron. **49**(5) (2013) 454-461.
[20] Z. Kuang, E. Lyon, H. Cheng, V. Page, T. Shenton, G. Dearden, Optics and Lasers in Engineering **90**, 275-283 (2017).
[21] T. Taira, S. Morishima, K. Kanehara, N. Taguchi, A. Sugiura, M. Tsunekane, 1st Laser Ignition Conf., Yokohama, Japan; LIC3-1 (2013).
[22] N. Pavel, A. Birtas, G. Croitoru, M. Dinca, N. Boicea, T. Dascalu, 5th Laser Ignition Conference, Optical Society, LWA4.3 (2017).
[23] S. Gupta, B. Bihari, M. Biruduganti, Q. Wang, R. Van Leeuwen, 4th Laser Ignition Conference, Yokohama, Japan, LIC8-2 (2016).