Laser ignited engines: progress, challenges and prospects

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Abstract: Laser ignition (LI) has been shown to offer many potential benefits compared to spark ignition (SI) for improving the performance of internal combustion (IC) engines. This paper outlines progress made in recent research on laser ignited IC engines, discusses the potential advantages and control opportunities and considers the challenges faced and prospects for its future implementation. An experimental research effort has been underway at the University of Liverpool (UoL) to extend the stratified speed/load operating region of the gasoline direct injection (GDI) engine through LI research, for which an overview of some of the approaches, testing and results to date are presented. These indicate how LI can be used to improve control of the engine for: leaner operation, reductions in emissions, lower idle speed and improved combustion stability.

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OCIS codes: (140.3538) Lasers, pulsed; (140.3440) Laser-induced breakdown.

References and links


1. Introduction

It is widely accepted that the IC engine will continue to be the main vehicle power plant over the next two decades, before significant displacement by alternative technologies takes place. Hence, as the global mobilization of people and goods increases, advances in combustion and...
after-treatment are needed to reduce the environmental impact of the continued use of IC engine vehicles. To meet environmental legislation requirements, automotive manufacturers continue to address two critical aspects of engine performance: fuel economy and exhaust gas emissions. New engines are becoming increasingly complex, with advanced combustion mechanisms that burn an increasing variety of fuels to meet future goals on performance, fuel economy and emissions. The spark plug has remained largely unchanged since its invention, yet its poor ability to ignite highly dilute air-fuel mixtures limits the potential for improving combustion efficiency. SI also restricts engine design, particularly in new GDI engines, since the spark position is fixed by the cylinder head location of the plug, and the protruding electrode disturbs the cylinder geometry and may quench the combustion flame kernel.

In this context, research into LI of IC engines seeks to examine its potential to improve combustion efficiency and stability compared to SI by igniting highly dilute air-fuel mixtures with comparatively low ignition energies and to initiate ignition away from the (cold) walls of the combustion chamber. With recent advances made in laser technology, the range of LI control parameters now includes laser pulse energy, pulse duration, wavelength, plus optical techniques and pulse selection for spatial and temporal distribution of laser energy in either single or multiple ignition events. The opportunity now exists to explore how the dynamic selection of these variables can be optimised for more efficient and cleaner combustion over the widest range of engine operating conditions. This paper discusses the key advances in LI of IC engines made by a number of research groups, including results from work carried out at UoL, which serve to illustrate the potential benefits of LI. The opportunities, challenges and prospects for future implementation of LI in next generation IC engines are then explored.

2. Laser ignition: review

The historic roots of LI research may be traced back to the first discovery of laser-induced optical breakdown by R.W. Terhune and associates [1] in 1962. There, the beam of a pulsed Q-switched ruby laser (of 10’s of MW peak power) was focused by a single lens in air to create a spark (plasma) comparable to an electrical discharge between electrodes. In reporting the discovery in 1963, Terhune dubbed his experimental set-up “the most expensive spark plug in automotive history”. The more fundamental aspects of LI science were the subject of reviews by Ronney, Phuoc and Bradley et al [2–4], which covered the early studies of laser induced breakdown in air, argon, helium, neon and nitrogen and on later work using methane, propane and butane as an ignitable gas, typically injected under pressure into a constant-volume combustion chamber. Aspects such as the evolution of shape and structure of laser induced spark and associated shock wave were studied. In 1978, Dale and associates became the first to report on experimental testing of LI in an IC engine [5], using a pulsed CO₂ laser, and a number of engine based studies then followed. For comprehensive reviews of work on laser ignited engines, the reader is referred to the recent papers by Tauer and associates [6] and (for a specific focus on IC engines) by Morsy [7] and the numerous references therein.

2.1 The LI process and mechanisms

The LI process requires conditions to be established for two basic steps to take place: spark formation (generally limited by breakdown intensity) and subsequent ignition (generally limited by a ‘minimum ignition energy’ or MIE). For example, it is possible either to deliver sufficient energy for ignition but with insufficient intensity (i.e. no spark forms), or to form a spark but with insufficient energy for combustion.

There are four principle mechanisms by which laser radiation can ignite combustible gas mixtures [2]: i/ Thermal initiation (TI); ii/ Non-resonant breakdown (NRB); iii/ Resonant breakdown (RB); iv/ Photo-chemical ignition (PCI). TI involves the gas mixture consuming laser energy to heat it to beyond the threshold ignition temperature [8,9]. TI is also possible by heating of a target surface in the combustion chamber. In NRB, which is similar to electric SI, the focused laser beam creates an electric field of sufficient intensity to cause dielectric
breakdown of the air-fuel mixture. The process steps are: multi-photon (MP) ionization of a few molecules to release electrons; ‘inverse bremsstrahlung’ to increase the electron kinetic energies, collision with and ionization of other molecules; electron avalanche and breakdown of the gas mixture [3, 4, 10]. At atmospheric pressure, the electric field strength necessary for laser induced breakdown (LIB) in gases is higher than for SI and, for ns duration pulses, the threshold optical intensity for NRB is of the order $10^{11}$ W/cm². Increasing the pressure to levels representative of real engine conditions reduces the MIE [8]. RB involves resonant absorption (by the atoms) of laser radiation at one or more specific wavelengths. iii/ differs from ii/ in that the free electrons needed for breakdown are created by two preceding steps: non-resonant MP photo-dissociation of a molecule, and then resonant photo-ionization of the atom created by the first step. MP absorption and ionization are thus key initiating steps for both ii/ and iii/. PCI involves single photon absorption and dissociation, usually requiring UV light. At high intensities, two-photon or MP absorption in matter can result in release of the accumulated energy as a single high-energy photon. In this way, resonant absorption at short wavelengths by the action of longer wavelength laser light is possible.

The most widely studied LI mechanism is NRB. It is similar to conventional electric SI in that plasma is produced which emits light, heat and a shockwave. However, laser-induced sparks are generally smaller in size, shorter in duration and have higher temperatures [11]. Typical temporal profiles of plasma light emission from a high energy (94mJ) ignition coil / fine wire spark plug and a focused Nd:YAG laser beam (10 mJ) are shown for comparison in Figs. 1(a)-1(b) [12]. The light was collected using a high speed photodiode with a wavelength response range of 200-1100 nm. As shown, the laser induced plasma has a significantly faster rise time and a duration approximately 100 times shorter than the coil and plug system.

Figure 1(c) shows that the light from the laser-induced plasma is significantly more intense than that for the SI case, despite the pulse energy being nearly one order of magnitude less.

### 2.2 Potential benefits of LI

Faster burns and increased dilution in combustion are two principal developments that could lead to higher indicated efficiency. The smaller volume plasma region and higher localised intensities reached in LI may also potentially enable further engine downsizing due to the more intense plasma being created in a reduced focal volume. The lack of an intruding electrode also reduces flame kernel quenching and results in shorter burn duration. In this context, the potential benefits of LI have been cited as: variation of ignition location in the cylinder [13]; no electrodes to disturb cylinder geometry or to quench a propagating flame kernel [14]; potential for engine control by varying ignition energy [15]; multiple ignition points in a cylinder [3, 16]; lower energy needed for combustion [17]; more stable combustion and increased engine performance [18]; reduced tailpipe emissions [5]; combustion of leaner air-fuel mixtures [15, 19]; shorter ignition delays and faster combustion [5]; and potential for
optical combustion sensing [12]. However, more experimental research is needed to build on the platform of fundamental LI science, to explore the potential benefits of LI applied to automotive IC engines from a perspective of enhanced combustion control.

2.3 Minimum ignition energy (MIE), focal volume and spark location

The minimum laser pulse energy needed to initiate a single ignition event provides a figure of merit for comparison with SI, and also points to the power requirements and physical scale of a LI system based on available laser sources. The MIE reported in the LI literature ranges from 0.15 mJ [20] to 1 J [5], but this large variation is partly due to the different optical arrangements and fuel types used in the various experiments. The MIE for conventional electric SI is around 50 mJ [21], although newer ‘fine wire’ spark plugs have energy outputs up to 80 mJ. The MIE is found to vary with pressure, temperature and fuel-air mixture ratio. For combustion to take place, the ignition process also requires an optimum spark kernel radius [4] and sufficient plasma intensity. The MIE will therefore vary with the focal length of the focusing optic and the focal point volume, so both are important factors in LI. The smaller the beam waist at focus, the higher the intensity for a given average laser power. At energies above the MIE, the spark plasma volume and position grows in the direction of the incoming laser light [11]. From Gaussian beam theory, a TEM$_{00}$ mode beam with a beam quality factor $M^2 = 1$ would be the most ideal, whereas for $M^2 \neq 1$ (higher order modes) the minimum waist size is given by:

$$d_{\text{min}} = \frac{4fM^2\lambda_0}{\pi D_L}$$

where $f$ is the focal length of the focusing lens, $\lambda_0$ is the laser wavelength and $D_L$ is the beam diameter incident on the lens. Multi-point LI is one of the key potential advantages that LI can offer over conventional SI. In a study by Morsy [16], a conical cavity technique was used to create up to three separate ignition sites and showed that multi-point LI significantly reduces total combustion time compared to single point LI. But, otherwise, there have been relatively few studies into practical methods of achieving multi-point LI and evaluation of its benefits.

3. Overview of key findings from LI research at UoL

The Laser Group of Dearden and Powertrain Control Group of Shenton have collaborated with the Ford Motor Co. (FMC) since 2003 in research on LI of gasoline vehicle engines. The aim has been lower fuel consumption and emissions by improved combustion. The laser engineering research has targeted novel LI concepts based on available (primarily lamp-pumped Nd:YAG) laser sources, parameters and optical techniques. A DTI Foresight Vehicle LINK project with FMC and GSI Group included the testing in 2006 of a system for one-cylinder LI of a port fuel injection (PFI) 4-cylinder GDI engine at FMC laboratories in Germany. This used a Spectron ‘Mini-Q’ Q-switched Nd:YAG laser and an optical plug substitute for the spark plug [13]. The tests confirmed that self-cleaning of the optical window by successive laser pulses – a concept previously explored as an extension of laser cleaning work at UoL [22] – was a key factor in enabling successful ignition. Successful demonstration of 4-cylinder LI at the UoL followed, with a few hours continuous operation being achieved using two synchronized Q-switched Nd:YAG lasers working in tandem. In one arrangement, the beam from each laser could be distributed or switched between two of the four cylinders, as in Figs. 2 and Figs. 3(a)-3(b) [18]. The variable pulse repetition rate (PRR) of the lasers gave additional ‘redundant sparks’ for self-cleaning of the optical plug window, as in Fig. 3(c). Key findings of the work included: identification of laser and optical design parameters needed for successful ignition and their effect on engine performance [15]; and improved combustion stability due to LI [23]. In contrast, experiments on the use of various types of optical fibre for beam delivery of Nd:YAG laser pulses [24] were less successful, with laser...
induced damage (at the fibre input interface) and energy/mode losses (due to bending and/or vibration) being identified as problems during the experiments.

Fig. 2. Schematic of one system developed at UoL for LI of a 4-cylinder PFI petrol engine [18].

Fig. 3. Photographs of UoL LI system, as illustrated in Fig. 2: (a) Laser and optics train (b) Engine mounted tuming mirrors; (c) Optical plug window removed after engine LI testing [18].

The UoL team were then funded by the Carbon Trust and FMC to investigate LI systems for next generation GDI engines using a special purpose single cylinder engine (SCE) designed and loaned by FMC and commissioned at the UoL. The SCE was used to assess the performance of LI relative to a state-of-the-art spark plug and coil ignition system. The setup included an eddy current dynamometer and optical bench with online and offline beam monitoring capability. Control of the engine and laser was achieved using a dSPACE real-time control system. A series of load, speed and air-fuel ratio (AFR) operating conditions were tested to compare the two ignition systems. A key outcome was that LI can outperform the spark plug and coil ignition system, in engine cycle-to-cycle stability and in extending the lean operating limit (i.e. requiring less fuel to achieve similar engine performance) [25].

Combustion stability: The engine's combustion stability was investigated in terms of cycle-to-cycle variation (CCV). Factors influencing CCV include the stochastic nature of gas mixing, stability of ignition timing and energies, and the chaotic formation of the flame kernel at combustion initiation. One of the main benefits associated with LI is a reduction in CCV, which results in improved engine stability. The indicators of CCV used here were indicated mean effective pressure (IMEP) and peak pressure position (PPP). IMEP is an indication of the average pressure exerted on the piston during the expansion stroke, defined as:
\[ IMEP = \frac{W_i}{V_d} \]  

where \( V_d \) is the displaced cylinder volume and \( W_i \) is the gross work delivered to the piston over the compression and expansion strokes, which is obtained by the circular integration of the pressure, \( P \), over these strokes, with respect to cylinder volume \([21]\):

\[ W_i = \oint P \partial V \]

The coefficient of variation in IMEP (COV\(_{\text{IMEP}}\)) is commonly used as an indicator of combustion stability and is defined as:

\[ \text{COV}_{\text{IMEP}} = \frac{\sigma_{\text{IMEP}}}{\langle \text{IMEP} \rangle} \]  

where \( \sigma_{\text{IMEP}} \) is the standard deviation and \( \langle \text{IMEP} \rangle \) is the mean of the IMEP respectively. The COV\(_{\text{IMEP}}\) is a percentage value defining the variation in indicated work per cycle. Vehicle driveability problems usually result when the COV\(_{\text{IMEP}}\) exceeds \( \approx 10\% \) \([21]\). For stoichiometric AFR operation (i.e. where the relative AFR, \( \lambda \) is 1, which for gasoline means the mixture is \( \approx 14.7 \) times the mass of air to the mass of fuel), the LI system was found to outperform the SI system in terms of reduced COV\(_{\text{IMEP}}\) \([25]\). Figure 4(a) compares the values of COV\(_{\text{IMEP}}\) over a wide range of ignition angles at 1500 rpm, 2.62 bar BMEP, and Fig. 4(b) compares the effect of load on COV\(_{\text{IMEP}}\) when operating at 1500 rpm at minimum advance for best torque (MBT).

![Fig. 4.](image)

Similar improvements were found for a range of loads and speeds when operating with stoichiometric mixtures. To identify possible reasons for the reduction in CCV, mass fraction burn (MFB) profiles and related metrics were studied. An averaged MFB plot calculated from pressure data is shown in Fig. 5(a), where it can be seen that the LI curve is of similar shape to that for SI, but exhibits a shorter ignition delay (\( 0 \) – \( 5\% \) MFB duration). Further analysis showed that the variance for this period was lower for LI, which could therefore be attributed to the lower COV\(_{\text{IMEP}}\). The shorter ignition delay of the LI system also resulted in an earlier PPP, which translated to lower ignition angles to achieve MBT compared to the SI system.
Dilute operation: LI was shown to improve the combustion stability at lean operation conditions ($\lambda > 1$) for both SCE and multi-cylinder engine operation. It was evident that at different operating conditions in the 1.6 litre PFI engine, similar levels of combustion stability were achieved by LI [12] (in all 4-cylinders) at leaner air-fuel mixtures to those of SI at the stoichiometric ratio. These improvements in stability for dilute operation have the potential to extend the lean limit of engines. Tests performed on the SCE at higher dilutions confirmed the improvements in stability. Only at significantly advanced ignition angles were infrequent and stochastically occurring misfires observed. This can be seen in Fig. 5(b), which shows the stability of the two ignition systems at $\lambda = 1.3$, 2.62 bar BMEP, 1500 rpm for a wide range of ignition angles. No measurements were made for the LI system for ignition angles greater than 44° before top dead centre (BTDC) due to the occasional misfires, which were thought to be due to the short duration of the laser-induced plasma. It was concluded that the relatively low cylinder pressures of the stochastic gas mixture, combined with the short duration laser plasma, resulted in less than 100% probability of generating a self propagating flame kernel. When operating at high levels of dilution with SI, it is common practice to increase the dwell time, which then increases the energy and duration of the resulting plasma. Hence, the laser pulse energy was increased to try to mitigate the misfires, but this showed no noticeable reduction in their occurrence. An explanation for this was that increasing the energy had no effect on the beam pulse duration. Further, since the breakdown threshold intensity (W/cm$^2$) for a given gas is constant, then the effect of increasing the energy acts only to achieve this breakdown prior to the desired focal position (minimum beam waist) [11]. Thus, increasing the laser energy may have the adverse effect of bringing the plasma location closer to the cylinder wall [12]. Operating GDI engines in stratified charge mode involves injecting the fuel relatively late in the compression stroke to create a fuel rich cloud close to the ignition location, but with a lean composition leading to little or no engine throttling. This offers future potential for improved efficiency and emissions, but stability and misfire problems inhibit extension of the stratified operating window. Multi-strike LI is therefore of interest to increase the probability of combustion and prevent misfire.

Emissions Control: Charge dilution with exhaust gas is now a key engine feature for achieving lower emissions (particularly NOx) and higher fuel economy. Increasing levels of exhaust gas recirculation (EGR) at part load operation can significantly improve the operating efficiency, since the reduced throttling lowers the pumping effort. The improvements in CCV observed under lean operation for LI should similarly translate to dilution with EGR.

Idle Speed Reduction: Vehicles in city traffic consume around 30% of their fuel whilst idling [26]. The lower CCV obtained with LI could translate to lower idle speeds, which could
then have a significant impact on the fuel economy of the vehicle. For example, a reduction in idle speed from 800 to 650 rpm could achieve fuel savings at idle of up to 24% [27].

Cold Start Performance: With no electrodes to quench the flame kernel, LI could offer improved cold start performance. Laser energies could be readily increased during cold start to improve the ignitability of the fuel. This benefit is expected to be particularly important for bio-fuels, which have poor start performance.

4. Opportunities and challenges for LI

4.1 MIE and laser wavelength tuning

The possibilities for reducing the MIE by tuning the laser wavelength to induce resonant / MP absorption mechanisms continue to be of interest, since lower MIE should in principle lead to more compact and cost effective LI systems in the future.

A number of studies have looked at combustion using laser wavelengths selected to match the absorption of different molecules. These included examination of the role of MP absorption in gas combustion by excimer [28], second harmonic pulsed ruby [11] and other forms of UV laser [29]. Whereas, IC engine based studies have mainly been limited to the discrete wavelengths provided by pulsed CO$_2$ lasers [9] and harmonics of the Nd:YAG laser [11,30]. The latter Nd:YAG laser studies concluded that more energy per pulse was needed to ignite at the second harmonic 532 nm compared with the fundamental 1064 nm. Bradley [4] suggested this was because the absorption of fuel-air mixtures is dependent on the radiation wavelength. Most fuel-air species only initially absorb either in the UV (below 160 nm) or the infrared (3–4 μm) [31], but if firstly ionised by a high intensity laser field they then become strong absorbers for inducing NRB. For gases such as air, lower breakdown intensities (and hence corresponding energies for a given spot-size) are typically reported for UV and shorter visible wavelengths [32]. Forch and Miziolek [29] studied the effect of wavelength on LI of hydrogen-oxygen gas mixtures, comparing the ignition by a tuneable UV laser with that of its Nd:YAG laser pump. Through resonant two-photon excitation and ionisation of H near 243 nm, a MIE as low as 0.55mJ was observed. In contrast, up to 40 times more laser energy was needed for ignition with either the fundamental or second harmonic outputs of the Nd:YAG laser, since these wavelengths were not absorbed by the gas mixture and so MP ionization was needed to initiate energy transfer. In this case, resonance enhancement in the formation of a ‘microplasma’ was reported to have given better ignition control compared to that by NRB.

From these and other earlier works, it is not clear whether tuning lasers to wavelengths other than their inherent discrete harmonic outputs generally gives more effective combustion by way of lower MIE. The potential benefits of lowering MIE values by wavelength tuning would also then have to be weighed against the practical viability of mass-producing specially tuned laser sources and other alternative options available for IC engine development (such as more readily absorbing fuel additives). Hence, this is an area for further study.

4.2 Deployment of laser energy

A number of recent advances in laser technology provide opportunities to further develop LI capabilities and knowledge through experiment, which are necessary for the future viability of laser ignited engines. The following are considered to be some of the most crucial aspects in the deployment of laser energy for engine ignition.

Laser source developments: Concepts being developed for engine LI include: compact lasers to mount directly on each cylinder head; locating the laser remotely and delivering the beam by optical fibre; and remote optical pumping of a miniaturised (spark plug sized) solid state laser. For research purposes, lamp-pumped Q-switched Nd:YAG lasers (and, to an extent, pulsed CO$_2$ lasers) provide a suitable range of output parameters – a typical parameter set being: 100 mJ pulse energy, 10 ns pulse length, 50 Hz pulse frequency and 5W average power. Clearly, however, they would not be viable for implementation in a future vehicle LI
system given their footprint, cost per unit and power supply / cooling requirements. The potential for future miniaturisation of LI technology is crucial for its viability (as will be its reliance on abundant, low environmental impact materials). To this aim, McIntyre and Woodruff developed a compact, saturable absorber Q-switched DPSS Nd:YAG laser with a pulse energy of several mJ, for LI of lean-burn stationary natural gas fuelled engines [33]. The group of Wintner have developed a compact, passively Q-switched, DPSS laser of high peak power, which uses Nd:YAG as the active medium and Cr4+:YAG as a saturable absorber medium [34]. This laser emits 6 mJ, 1.5 ns long pulses at 1064 nm with a TEM00 beam mode. The group of Byer successfully scaled various DPSS lasers to high average powers, including those based on ceramic Nd:YAG laser materials [35]. Kroupa et al [36] demonstrated a robust, miniaturized, diode-pumped Nd:YAG laser, designed for LI in IC engines and with passive Q-switch generating 25 mJ at 3 ns and repetition rates of up to 150 Hz. The group of Taira recently developed a composite ceramic, passively Q-switched laser of the size of a spark plug [37]. This has been used in successful tests of LI in a combustion bomb, delivering pulse energies of a few mJ. Such ceramic lasers are attractive for their robustness under conditions of high temperature, high pressure variation. Pulsed fibre lasers are also a potential candidate for future LI. Since the active fibre is not usually the end delivery fibre, the ability of both the active and passive fibre elements to carry high pulse energies without damage and with low losses becomes important. Pulse energies of ~1mJ are now available in commercial units and laser spark formation with a fibre laser, delivering 0.55 mJ pulses through a photonic crystal fibre (PCF), has already been demonstrated [38].

Window ‘sooting’: Applying LI to an IC engine, the inner optical surface (window, lens, fibre) through which the laser beam passes to enter the combustion chamber will be exposed to the combustion process and conditions. Coating of this optical surface with combustion deposits (‘sooting’) has been a major drawback in attempts to demonstrate viability of LI in engines, since a build up of deposits with successive engine cycles degrades the transmission of laser energy. Despite this, several research groups have reported successful demonstration of LI, wherein an efficient ‘self-cleaning’ (SC) of the window surface by the pulsed laser radiation was observed [18,38,39], thus sustaining transmission through the optical pathway. Figure 2(c) shows an example of a window used in UoL work [18]. The effectiveness of the SC mechanism and progressive cleanliness of the surface was analysed in detail by Ranner et al [38], who also reported on the effect of different pulse sequences. Using 5ns long laser pulses, energy fluences greater than a threshold value of 10mJ/mm² were needed at the window to keep its surface free of deposits. These results are encouraging and provide the basis to evaluate the viability sustaining long periods of LI operation under high duty test conditions.

Laser induced optical damage: It is clear from research to date that the laser intensities necessary for successful LI in IC engines are high enough to induce material damage in the various optical media being used. Careful optical design, material preparation and selection of laser beam parameters are needed to reduce the probability of damage occurring. Catastrophic damage may result from highly localised stress due to thermal shock, or self-focusing effects, or ablation initiated by high field concentration at the site of surface imperfections and contamination. Close to the damage threshold, a sudden change from more subtle forms of longer-term degradation to catastrophic damage is likely and often unpredictable. Approaches to mitigating the risk of damage include seeking lower MIE through LI mechanisms other than NRB (which requires the highest intensities) and using pulse durations longer than 10 ns (drawing upon, for example, the experience of beam delivery in laser cleaning studies).

Optical fibre beam delivery: Optical fibres are potentially attractive for delivering laser energy to the engine from a remote laser source. Benefits include flexibility of beam pathway design, reduction in the effect of engine vibration on optical alignment and stability, and space savings on system parts needed to be mounted on the engine cylinder head. In LI research, fibre delivery has been studied either to provide a pathway from the LI source
directly to the combustion chamber, or for remote pumping of miniaturised laser cavity/media located at the engine. Figure 6 illustrates some of the main types of optical fibre considered for LI. Threshold laser intensities for inducing material damage in multimode solid core fibres are typically <5GW/cm², which limits their potential for use in LI. However, Joshi et al recently reported work on large clad step-index fibres (clad-core ratio > 1.1) [40] exhibiting a damage threshold >100GW/cm². By lengthening the Q-switched Nd:YAG laser pulse from low ns to high ns (e.g. 10ns to 50ns), the fibres successfully delivered pulse energies >20mJ and gave 100% reliability of LI. Over-bending of optical fibres can result in unwanted energy coupling to higher order modes and transmission losses. Some beam delivery studies on solid core (step-index) fibres reported a detrimental effect of bending [24] and vibration-induced localised stresses [12] on the beam intensity profile and transmission, which justifies further evaluation.

Fig. 6. Types of optical fibre considered for LI, from left to right: step index; graded index; multi-layer hollow glass; hollow core; photonic crystal (or band-gap).

Hollow-core optical fibres look particularly promising for beam delivery in LI. Matsuura et al developed hollow-core fibres for low-loss, high peak power delivery of second, third, and fourth harmonic wavelengths of a Q-switched Nd:YAG laser [41]. These were hollow glass fibres, with an inner surface coating of either polymer/silver (for 532nm) or aluminium (for both 335nm and 266nm), and led to the first reported demonstration of laser spark ignition by fibre delivery in conjunction with Yalin and associates at Colorado State University [42].

Laser pulse frequency and timing: The timing of ignition events in each engine cycle is crucial for both successful combustion and optimum performance. For a single event per cycle in each cylinder of a typical 4-stroke engine, the event frequency must vary between ~8.3 Hz at 1000rpm and 25Hz. Thus, a variable frequency laser or a high-frequency laser with suitable ‘pulse picking’ capability would be essential for synchronising over a full range of engine speeds. In 4-cylinder engine LI testing at UoL [26], it was also found that an extra laser spark on the exhaust stroke further enhanced SC of the optical plug window to help maintain optical transmission for the next laser pulse on the compression stroke (this also then reduced the required MIE). The SC effect and surface cleanliness were analysed in detail by Ranner et al [38], who also reported on the beneficial effect of using different pulse sequences.

User safety: the approval of LI systems for use in next generation engines will require the engineering of robust safety measures to minimise the risk of exposure to harmful levels of laser radiation during operation, maintenance, or as a result of damage. LI systems will need to be engineered to meet Class 1 hazard classification under normal operation. As always, the risk of eye damage is of highest concern – even the intensity of the pump light supplied to a passively Q-switched laser discussed earlier would far exceed maximum permissible exposure (MPE) levels. During system maintenance or servicing, assessment of the risk of accidentally igniting flammables with concentrated levels of radiation would also be necessary. Innovative concepts will be required to address these challenges. One example of work in this area is that by Zhao and associates who developed and demonstrated a fibre-based optical interrupter for high peak power transfer in LI systems [43].
4.3. Dynamic control of ignition location in the combustion chamber

The selection of ignition point location(s) in the cylinder requires a detailed study to establish the benefits of this variable with LI. By modulating light from pulsed solid state lasers, the spatial and temporal control of intense optical energy delivery in LI is now a possibility and needs to be studied for its potential to give reliable ignition under high levels of dilution or lean stratified charge modes of engine operation. For ignition of homogeneous mixtures in engines, previous studies suggest the lean limit of flame propagation may be extended by a more central spark location, increased spark duration and by multiple sparks – LI can deliver all these needs. Increased engine efficiency is also obtained by using high levels of dilution, therefore a key development for next generation engines is spray guided GDI, in which fuel is injected into the chamber in a series of spray jets. In stratified charge mode, there is potential to increase fuel efficiency by using lean mixtures, if reliable ignition of these can be obtained. Extending spark duration increases the amount of exhaust gas recirculation (EGR) that an engine can tolerate without misfires [25] and multiple ignition points is one way of achieving this. With SI, the limited cylinder head volume constrains engine design to a maximum of two plugs and only two (fixed) ignition points. Addressing the limitations of SI, therefore, LI provides a way of delivering multiple ignition points, in either fixed or dynamically varying positions. If operating above the MIE threshold, the observed growth in volume and location of the plasma in the direction of the incoming beam would need to be taken into account in controlling the effective ignition point and in keeping it away from the chamber walls [11].

4.4 Combustion sensing using the optical pathway

The use of LI in IC engines provides opportunities for optical in-cylinder combustion sensing for accurate and rapid feedback control, by virtue of the self-cleaned optical pathway travelled by the laser beam. The plasma created in the laser spark naturally lends itself to laser-induced breakdown spectroscopy (LIBS) diagnostics. LIBS has been used by Ferioli and associates [44] to measure the equivalence ratio of a spark-ignited engine (over the range 0.8-1.2), from the spectral emission features of the combustion elements. For averaged measurements, the C/N and C/O peak ratios were found to be successful measurement metrics compared to a standard exhaust gas oxygen analyzer. Joshi et al [45] reported on the first demonstration of the simultaneous use of laser sparks for engine ignition with LIBS measurement of in-cylinder equivalence ratios. By collecting optical emission from the igniting laser spark through the optical plug, and analyzing cycle-by-cycle spectra, a linear correlation ($R^2 > 0.99$) between spectral line intensity ratio and equivalence ratio was found, suggesting a potentially useful engine diagnostic method for cylinder-resolved equivalence ratio measurements. These results show that techniques such as LIBS, pattern recognition using photo detectors and advanced signal processing such as on-line principal component analysis (PCA) and neural networks could be investigated as the basis for real-time feedback control of combustion.

5. Future prospects

LI offers a significant number of opportunities for improved combustion control in engines through the method of delivery of laser energy to the focal position(s), new generation laser parameters and optical sensing. In order to fully exploit the benefits of LI, these topics need further investigation before an optimised control scheme can be found. The opportunity for feedback sensing and control make LI particularly exciting in the following areas:

Optimised engine design: The entry position of the ignition source on the cylinder head of the engine becomes far less critical with LI since optical elements can be used to obtain the desired ignition location. Furthermore, the entry for the laser beam could be made considerably smaller than that required for a spark plug. As such, there is significant scope for future cylinder head designs to better optimise the injection location or increase valve sizes.
Dynamically controlled variable ignition location: The position of the ignition location can be varied by focusing the laser beam with optical elements to the required position along its optical axis, to allow deeper ignition location than with a spark plug. The compact ceramic laser discussed earlier also provided three-point ignition at preset locations, with control of the pulse timing of the laser-array achieved by varying the pump energy to each of the individual pumping lines [46]. Diffractive optical elements can be used to focus a single laser beam to multiple locations within the combustion chamber. Variable telescopes offer a relatively simple method of dynamically varying the ignition position. Emerging technologies have also included ‘liquid’ lenses which can dynamically change their focus under electrical stimulus. Further development of such technologies could allow the focal position to be changed to suit the operating condition of the engine. In GDI engines for example, this would allow for optimal ignition location matched to either homogenous or stratified charge modes.

Temporally controlled multiple ignition timing: With the development of new high frequency (>kHz) laser technologies, including pulsed fibre lasers, it is anticipated that future LI systems will be capable of selecting and delivering multiple pulses within the combustion cycle. Similar repetitive discharge circuits for spark plugs have been researched for highly dilute and stratified charge modes of operation; however, a high frequency laser system would have the added advantages of accurate control of the number and timing of the pulses and the ability to deliver shorter duration spark events if needed.

Opportunities for additional feedback sensing: LI potentially provides an optical pathway into and out of the engine cylinder, due to the SC mechanism. This should allow the light generated during the combustion process to be monitored and the ‘light-signature’ examined for real-time estimation of the combustion temperature, emission species, AFR and pressure through optical sensing, signal processing and pattern recognition methods. Alternative laser based combustion monitoring methods include laser-induced fluorescence and laser-induced incandescence, although these would be more complex and costly to implement. In principle, all of these techniques can be used for on-line, real-time feedback control of the combustion.

7. Conclusions

Research to date on LI in engines has demonstrated improvements in combustion stability, as measured by \( \text{COV}_{\text{IMEP}} \). With proper control, these improvements can enable engines to be run under leaner conditions, with higher EGR concentrations, or at lower idle speeds without increasing the noise, vibration and harshness characteristics of a vehicle. LI gives significantly shorter plasma duration compared to SI. With the recent development of higher average power and higher pulse frequency lasers, it is expected that a multi-strike LI system and associated combustion control can reduce the probability of misfires under high levels of dilution. The prospects for LI are also particularly exciting from a control perspective, from optical sensing of the in-cylinder combustion made possible through SC of the laser beam pathway, to the array of possible ignition activation and control mechanisms. It is anticipated that this, combined with the capability to control the ignition location and timing, will play a significant role in optimisation of future engines by dynamic feedback control.

Acknowledgments

The current work at UoL is supported by the UK’s Engineering & Physical Sciences Research Council (EPSRC), FMC and Cambustion Ltd. The authors acknowledge the UK Government (through its former Department of Trade and Industry), the Carbon Trust and FMC for their support of earlier LI research at the UoL. The authors would also like to acknowledge the following for their technical contributions: Paul Dickinson, Jack Mullett, Robert Dodd (formerly of the UoL LI team); Derek Neary (School of Engineering, UoL); Andy Scarisbrick, Jon Caine, Oliver Berkemeier, Rob Helle-Lorentzen, Michael Czekala and Joe Schim (FMC).