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# Effects of laser parameters on laser ignition in an internal combustion engine

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**Abstract.** Recent research in laser-induced ignition (LI) of air-fuel mixtures in internal combustion (IC) engines has shown there to be many potential advantages over conventional electrical spark ignition (SI). Spark plugs offer only limited possibilities for optimising engine efficiency, due to their fixed position within a cylinder and the protrusion of electrodes which disturb the cylinder geometry and can quench the flame kernel. Laser radiation is non-invasive and has greater flexibility in terms of the ignition position, allowing the possibility of multi-point ignition. Other potential benefits of LI include: reduced emissions, more stable combustion and lower idle speeds, when compared to conventional SI. This paper reports on the current research being undertaken at The University of Liverpool, which examines the effects of engine combustion performance and stability when specific laser parameters (beam energy, minimum spot size and focal length/volume) are varied. A Q-switched Nd:YAG laser operating at the fundamental wavelength 1064 nm was used to ignite gasoline and air mixtures in one cylinder of a 1.6 litre IC engine, where the remaining three cylinders used conventional SI. A direct comparison between LI and conventional SI is presented in terms of changes in coefficient of variability (COV) in indicated mean effective pressure (IMEP) and the variance in the peak cylinder pressure position (PPP).

## 1. Introduction

Previous studies on laser ignition (LI) have largely investigated the fundamental processes of laser induced gas breakdown for the application of gas reciprocating engines; where methane, hydrogen and oxygen are the most commonly used gases. However, relatively few studies have concentrated on LI of automotive gasoline IC engines [1-4], which is the main focus of this paper. Research conducted at The University of Liverpool [5, 6], is to the authors' knowledge, the only LI research to use an unmodified production automotive engine.

A review of the literature has shown there to be four principle LI mechanisms [7]: non-resonant breakdown ignition, resonant breakdown ignition, thermal ignition and photochemical ignition. Non-resonant breakdown is the mechanism by which LI is performed in the tests presented in this paper

and is the most widely used and studied form of LI. The electrical field of a focused laser beam is adequate to cause dielectric breakdown of the fuel, similar to conventional electric spark ignition (SI), using laser irradiances in excess of  $10^{11}$  W/cm<sup>2</sup>. This process generally begins with multi-photon ionization of a few molecules, which leads to the release of electrons that can then readily absorb more photons from the laser source. This in turn increases the kinetic energy of these released electrons, which then collide with other molecules and ionise them, leading to an electron avalanche and breakdown of the combustible gas mixture.

The main aims of the research shown in this paper are to investigate the effects of laser parameters on LI and assess the performance of LI against conventional SI. This is achieved by examining the engine's combustion stability in terms of cycle to cycle variation (CCV), in two cylinders (one ignited by a conventional spark plug and the other by an Nd:YAG laser beam). CCV is due to variation in the air/fuel ratio near the ignition point, ignition timing, and formation of the flame kernel at combustion initiation. Benefits of LI associated with engine performance are most likely to be a result of reduced CCV. The indicators of CCV used in this work were indicated mean effective pressure (IMEP) and peak pressure position (PPP), which have the units of bar and degrees respectively. IMEP is extensively used in engine calibration and the coefficient of variation in IMEP ( $COV_{IMEP}$ ) is used as an indicator of combustion stability. The COV of IMEP is commonly used in industry and is defined as:

$$COV_{IMEP} = \frac{\sigma_{IMEP}}{imep} \times 100 \quad (1)$$

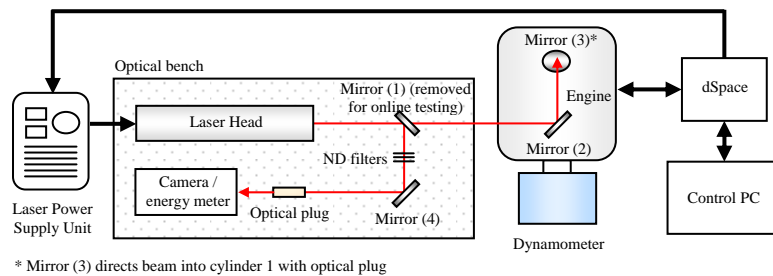
where  $\sigma_{IMEP}$  is the standard deviation in IMEP, and  $imep$  is the mean IMEP. The PPP is the crank angle in degrees after top dead centre (ATDC), at which the peak pressure occurs for each combustion event. The optimum PPP is usually around 16° ATDC, but is mainly dependent on engine geometry. The variance in PPP ( $Var_{PPP}$ ) has been demonstrated as an indicator of CCV [8] and is defined as:

$$Var_{PPP} = (\sigma_{PPP})^2 \quad (2)$$

where  $\sigma_{PPP}$  is the standard deviation in PPP. Lower values of  $COV_{IMEP}$  and  $Var_{PPP}$  indicate reduced CCV, and hence better combustion performance and stability [9].

## 2. Experimental

The laser used for the LI experiments was a 'Mini-Q' Q-switched Nd:YAG, manufactured by GSI Group, operating at the fundamental wavelength of 1064 nm. The laser was operated in single mode giving a near Gaussian beam profile, where the beam quality factor  $M^2$  was calculated to be <2 for repetition rates between 1 and 20 Hz. The pulse width was measured using an oscilloscope and a photodiode, to be 10 ns using the full width half maximum. A schematic of the experimental setup can be seen in figure 1, which shows two legs, one for offline testing and the other for online testing.



**Figure 1 Experimental setup for offline and online laser ignition testing.**

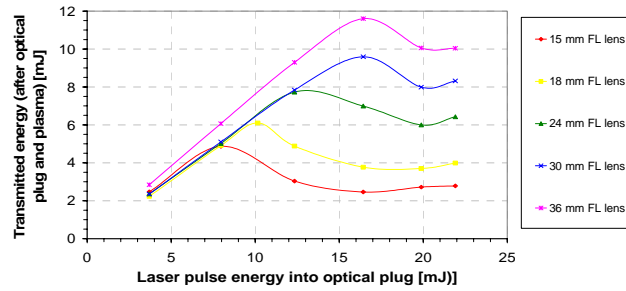
Five different focal length (FL) lenses (15, 18, 24, 30 and 36 mm) were tested individually in a specifically designed optical plug. These were all uncoated BK7 plano-convex lenses, apart from the 36 mm FL lens, which had a visible to near infrared coating. An uncoated sapphire window was sealed

at the bottom of the optical plug for each of these different lenses. The minimum beam waist produced by each lens was positioned at 4 mm from the bottom of the plug (which is at the same location as the electrical discharge of the spark plugs), as this was found from previous testing to be the optimum LI position for this engine. Mirror (1) was installed on the optical bench for offline testing to direct the beam into the optical plug, as shown in figure 1. The plug was at a beam path length of 1.4 m from the laser head which was the same distance as it was for the online tests. An energy meter (Gentec ED 200 head and Solo PE monitor) was used to measure the laser pulse energies at various laser drive levels, taking the average energy of a 200 pulse sample. The energies were measured before each optical plug on the bench, starting with 4 mJ, then increasing by set increments up to a maximum of 23 mJ. The subsequent energies transmitted through the plugs for each energy increment were also measured by placing the energy meter at 40 mm after the plug, accounting for the plasma produced. From these tests, the transmissions of the optical plugs were measured in order to calculate the actual beam energy that would be delivered inside the engine's cylinder. An Electrophysics Micro-viewer 7290A camera system was used to measure the minimum spot sizes produced by the different FL lenses in the optical plug to an accuracy of  $\pm 5 \mu\text{m}$ . These minimum spots were used with the recorded energies to calculate laser irradiances in  $\text{W}/\text{cm}^2$  for the various settings. The camera was also used to measure the beam sizes on the lenses in the optical plug for laser drive levels between 40 and 100 %, to ensure that these were similar, as a variance in beam size would affect the minimum spots produced.

For the online testing, the laser system was controlled through a dSpace DS1005 card in a bus linked expansion box using a Simulink laser timing model designed and run through MATLAB. The IC engine used was an unmodified Ford Zetec 1.6 litre that had 4 cylinders and 16 valves, with aspirated port fuel injection (PFI), which operated in a homogenous ignition mode. The engine was connected to a low inertia dynamometer, to provide a load to simulate real working conditions. Cylinder pressure data was taken from cylinders 1 and 4 for comparison of LI to SI combustion cycles. During testing, cylinder 1 was fired optically using the laser, while cylinders 2, 3, and 4 were ignited using conventional spark plugs. For each cycle, the Simulink model sent a signal via dSpace to the laser to activate the flashlamp, where a set time period later the Q-switch was triggered internally by the laser power supply unit. The conventionally fired cylinders were ignited at the crank angle corresponding to the triggering of the laser Q-switch (i.e. all 4 cylinders fired at the same time). For each optical plug tested online, the laser energy was reduced to find the minimum ignition energy (MIE) for misfire free combustion. The energy was then increased in increments up to a maximum of 23 mJ, where the steady state values (assumed over 300 cycles [9]) of  $COV_{IMEP}$  and  $Var_{PPP}$  for cylinders 1 and 4 were recorded for each energy level. Each test was performed at an engine speed of 1500 RPM and each cylinder was fired  $30^\circ$  before top dead centre. The results were only recorded once the engine had warmed up (coolant temperature  $>80^\circ\text{C}$ ), to ensure that the conventionally fired cylinders were operating optimally.

### 3. Results and Discussion

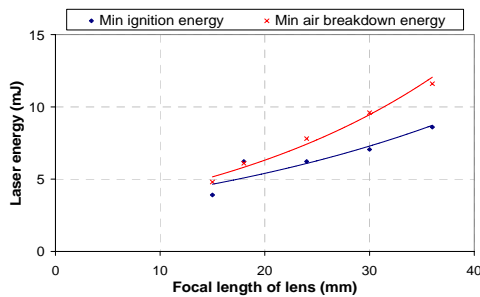
It was found from characterisation of the laser that there was a minimal effect on the output beam size when the energy drive level on the laser power supply unit was increased. The mean beam radius at 1.4 m from the laser head, for laser drive levels of 40 to 100 %, was found to be  $1290 \mu\text{m}$ , with a standard deviation of  $35 \mu\text{m}$ . It was therefore acceptable to assume that the minimum beam spot diameters produced by the different plug lenses were constant through the energy range tested. These were found to be 20, 22, 26, 30 and  $36 \mu\text{m}$  for the 15, 18, 24, 30 and 36 mm FL lenses respectively. The offline results for increasing the pulse energy into the five optical plugs are illustrated in figure 2, which shows the transmitted energies through the plugs. The peak of each curve indicates the minimum energy required to cause optical air breakdown at atmospheric pressure for the respective FL lenses. After this point, plasmas were formed which absorbed the incident energy. It can be seen from figure 2 that at the higher plasma producing input energies, the transmitted energy through the optical plugs and plasma becomes fairly constant, which indicates that a percentage of the incident energy is being absorbed by the plasma.



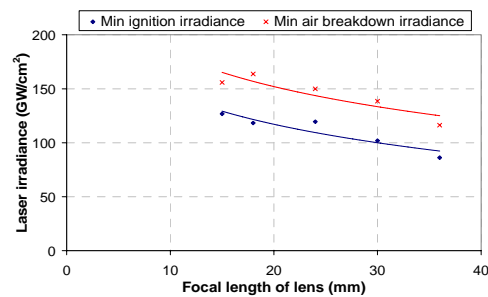
**Figure 2 Transmitted energy through the five optical plugs and subsequent plasmas produced**

However, there will be an energy point where the plasma becomes saturated, which was not found, due to the energy limitations of the laser. It is worth noting that when the optical plug is used online, the proportion of the laser energy that is not absorbed by the plasma would impinge on the piston head and may over time cause damage. However, the laser irradiance on the piston head would vary depending on a number of variables such as laser energy, FL of lens, focal point location, spark timing and cylinder geometry. This is therefore an issue which will be addressed in future research.

The minimum energies needed to produce dielectric breakdown in air at atmospheric pressure for the different FL lenses used in the optical plugs can be seen in figure 3, along with the MIEs required for misfire free LI combustion obtained from the online results. It can be seen that more energy is required for ignition/breakdown using longer FL lenses, due to the larger minimum waists produced. Figure 3 also shows the energies required for ignition in the engine cylinder are lower than for air breakdown, due to the higher pressures and temperatures. The lowest MIE for the online LI experiments was found to be 4 mJ when using the 15 mm FL lens in the optical plug. This energy is much lower than the energies used by standard ignition coils, which are in the range of 30-50 mJ [9].



**Figure 3 Minimum energy required for ignition and air breakdown for various focal length lenses**

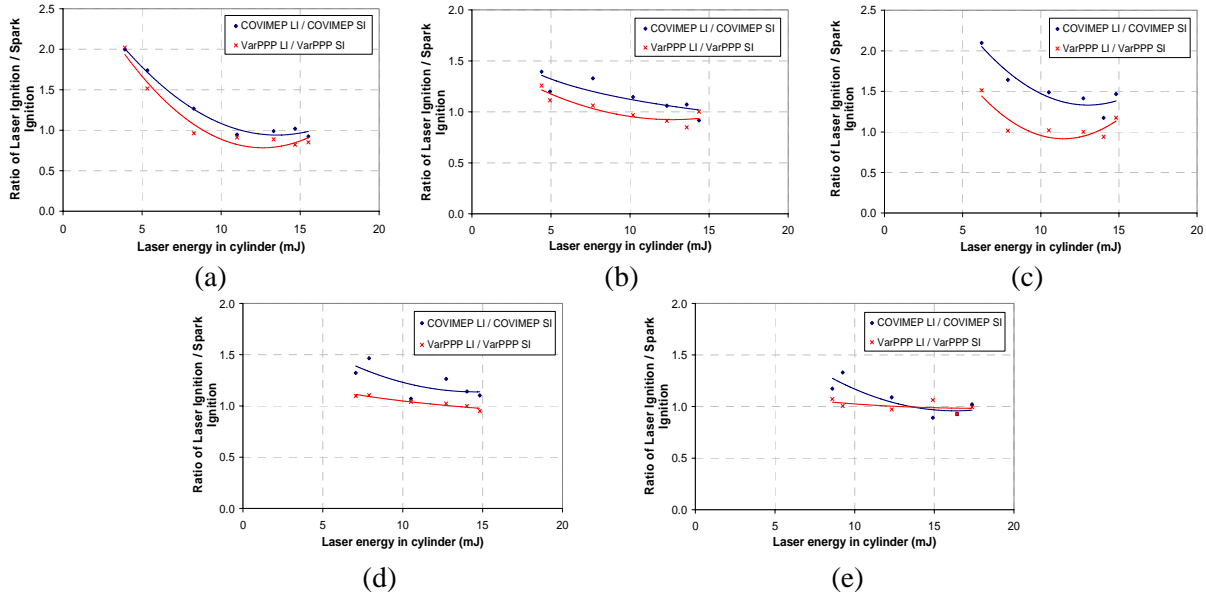


**Figure 4 Minimum irradiance required for ignition and air breakdown for various focal length lenses**

The minimum laser irradiances required for LI and for air breakdown for the different FL lenses were calculated and can be seen in figure 4, which again shows that laser irradiance levels required for ignition are lower than for air breakdown. Interestingly though, the irradiance required for both ignition and air breakdown decreases with longer FL lenses. This is most likely due to the fact that longer FL lenses have greater Rayleigh ranges (depth of focus) and hence have greater focal point volumes. Consequently, this means that the maximum laser irradiance at the focal point will interact with a larger volume of fuel, therefore increasing the probability of breakdown. The minimum irradiance will however reach a threshold limit as lens FL increases, as there will be a threshold value at which dielectric breakdown of the air/fuel mixture occurs. Therefore, at this irradiance threshold, the MIE required would become exponential as lens FL increases.

To directly compare the performance of the laser ignited cylinder with the conventionally ignited cylinder, the  $COV_{IMEP}$  and  $Var_{PPP}$  values for LI were divided by the  $COV_{IMEP}$  and  $Var_{PPP}$  for SI respectively, to obtain a ratio for each of the optical plug lenses; whereby any ratio values  $<1$  would

indicate that the laser is operating better than the spark plug. These ratios for both  $COV_{IMEP}$  and  $Var_{PPP}$  were plotted against the laser energy delivered inside cylinder 1, which are illustrated in figure 5 (a)-(e) for the five different FL lenses used in the optical plug.



**Figure 5 Effects of increasing laser energy in cylinder 1 on the ratios of  $COV_{IMEP}$  of laser ignition /  $COV_{IMEP}$  of spark ignition and  $Var_{PPP}$  of laser ignition /  $Var_{PPP}$  of spark ignition, when using different focal length lenses in the optical plug: (a) 15 mm, (b) 18 mm, (c) 24 mm, (d) 30 mm and (e) 36 mm**

The most successful LI results were from using the 15 mm FL lens, as for energies between 12 and 16 mJ the ratios for both  $COV_{IMEP}$  LI /  $COV_{IMEP}$  SI and  $Var_{PPP}$  LI /  $Var_{PPP}$  SI are below 1, which signifies that LI is performing better than SI. This implies less cyclic variation and hence improved combustion performance and stability. Figure 5 (a)-(d) illustrates that the ratios of  $Var_{PPP}$  LI /  $Var_{PPP}$  SI are lower than the ratios of  $COV_{IMEP}$  LI /  $COV_{IMEP}$  SI. However, for the 36 mm FL lens (figure 5(e)), the ratios for  $COV_{IMEP}$  LI /  $COV_{IMEP}$  SI and  $Var_{PPP}$  LI /  $Var_{PPP}$  converge towards 1, indicating similar, if not better performance than SI. Reducing the FL of the lens used in LI below 15 mm may make combustion more susceptible to possible variations in the homogenous air/fuel mixture as the focal point volume is reduced, as discussed earlier.

It can be seen from figure 5(a)-(e) that there is a general trend for all five FL lenses, whereby the ratios of  $COV_{IMEP}$  LI /  $COV_{IMEP}$  SI and  $Var_{PPP}$  LI /  $Var_{PPP}$  SI became lower with increased energy, until a point where the ratios tend to level out. This would indicate that greater combustion performance and stability is achieved by higher laser energies up until a threshold energy level, above which there is no significant improvement. Similar observations have been reported by Alger *et al* [10] who studied LI of propane. The reasons for greater combustion performance and stability with increased laser energy could be due to the plasma produced in the cylinder absorbing the extra energy, as discussed previously for the offline results. Chen *et al* [11] suggest that when more laser energy is deposited into an optically produced plasma, the plasma tends to expand in size instead of becoming hotter or denser. Larger plasmas produced in the cylinder can achieve faster flame kernel growth, which reduces cyclic combustion variability [9].

Too much laser energy delivered in the cylinder may have undesirable effects on combustion and stability. Chen *et al* [11] state that if the incident laser energy is higher than the breakdown threshold of the ambient gas, then breakdown can be initiated at an earlier location before the pulse reaches the focal point. Therefore, the higher the incident energy, the further away the plasma moves from the focal point. Previous LI research at The University of Liverpool has found that poorer combustion and

higher cyclic variations occurred when the focal point position is moved closer to the top cylinder wall. Furthermore, it is widely known that optical breakdown of gases produces shockwaves. Therefore, excessive laser energy delivered into the cylinder would cause higher pressure shockwaves, which may have adverse effects on combustion stability, as these could affect the initiation and propagation of the flame kernel or even extinguish it. There are also laser energy limitations to account for, as well as damage threshold limits of the optical components (i.e. focusing lens and window). Unfortunately, these effects mentioned above were not observed due to the energy limitations of the laser used.

#### 4. Conclusions

Successful LI of homogenous gasoline and air mixtures have been demonstrated in one cylinder of an unmodified production automotive engine, using a Q-switched Nd:YAG laser. The results presented show a direct comparison of combustion performance between a laser ignited cylinder and a conventionally ignited cylinder, where the results are displayed as ratios of  $COV_{IMEP}$  and  $Var_{PPP}$ . The major findings from this research were that LI performed better than SI in terms of combustion stability, when using energies between 12 and 16 mJ with a 15 mm FL lens to focus the beam. The lowest minimum laser energy required for misfire free combustion was found to be 4 mJ per pulse, also using the 15 mm FL lens in the optical plug. This compares to ~30 mJ in a ~1 ms electrical pulse for conventional SI. The minimum laser irradiance required for LI was found to reduce when longer FL lenses were used, and improved combustion performance and stability was achieved by using higher laser energies.

#### References

- [1] Dale, J. D., Smy, P. R. and Clements, R. M. (1978) "Laser ignited internal combustion engine An experimental study", SAE, 780329.
- [2] Alger, T. A., Mehta, D. and Chadwell, C. J. (2004) "Laser ignition in direct injection engines", Southwest Research Institute – Internal Research and Development, Available from: <http://www.swri.org/3pubs/ird2004/synopses/039354.htm>, [Accessed on July 2006].
- [3] Lackner, M., Winter, F., Graf, J., Geringer, B., Weinrotter, M., Kopecek, H., Wintner, E., Klausner, J. and Herdin, G. (2004) "Laser ignition in internal combustion engines - A contribution to a sustainable environment", Proc. 14<sup>th</sup> IFRF Members Conference, pp. 1-18.
- [4] Liedl, G., Schuöcker, D., Geringer, B., Graf, J., Klawatsch, D., Lenz, H. P., Piock, W. F., Jetzinger, M. and Kapus, P (2005) "Laser induced ignition of gasoline direct injection engines", Proc. SPIE, Vol. 5777, pp. 955-960.
- [5] Carroll, S., Dodd, R., Shenton, A. T., Dearden, G., Scarisbrick, A. and Keen, S. (2005) "Laser ignition in an automotive engine: analysis and control of C.O.V. in I.M.E.P. and P.P.P.", JSAE Annual Congress proceedings, 165.
- [6] Dodd, R., Mullett, J. D., Carroll, S., Dearden, G., Shenton, A. T., Watkins, K. G., Triantos, G. and Keen, S. (2005) "Laser ignition of an IC test engine using an Nd:YAG laser and the effect of key laser parameters on engine combustion performance", ALAC 2005 Proceedings Volume 3: Product Engineering & Manufacturing, ISBN: 1554-2971, pp. 104-111.
- [7] Ronney, P. D. (1994) "Laser versus conventional ignition of flames", Optical Engineering, Vol. 33, pp. 510-522.
- [8] Triantos, G., Shenton, A.T. and Carroll, S.D. (2004) "Minimum variance control of cylinder peak pressure position", IFAC AAC04.
- [9] Heywood, J. (1988) "Internal combustion engine fundamentals", McGraw-Hill, Inc. New York.
- [10] Alger, T. A., Mehta, D. and Chadwell, C. J. (2005) "Laser ignition in a pre-mixed engine: The effect of focal volume and energy density on stability and the lean operating limit", SAE international, 2005-01-3752.
- [11] Chen, Y. L., Lewis, J. W. L. and Parigger, C. (2000) "Spatial and temporal profiles of pulsed laser-induced air plasma emissions", JQSRT 67, pp. 91-103.