Laser induced ignition

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ABSTRACT

Nowadays, combustion engines and other combustion processes play an overwhelming and important role in everyday life. As a result, ignition of combustion processes is of great importance, too. Usually, ignition of a combustible material is defined in such a way that an ignition initiates a self-sustained reaction which propagates through the inflammable material even in the case that the ignition source has been removed. In most cases, a well defined ignition location and ignition time is of crucial importance. Spark plugs are well suited for such tasks but suffer from some disadvantages, like erosion of electrodes or restricted positioning possibilities. In some cases, ignition of combustible materials by means of high power laser pulses could be beneficial. High power lasers offer several different possibilities to ignite combustible materials, like thermal ignition, resonant ignition or optical breakdown ignition. Since thermal and resonant ignitions are not well suited on the requirements mentioned previously, only optical breakdown ignition will be discussed further. Optical breakdown of a gas within the focal spot of a high power laser allows a very distinct localization of the ignition spot in a combustible material. Since pulse duration is usually in the range of several nanoseconds, requirements on the ignition time are fulfilled easily, too. Laser peak intensities required for such an optical breakdown are in the range of 10^{11} W/cm^2. The hot plasma which forms during this breakdown initiates the following self-propagating combustion process. It has been shown previously that laser ignition of direct injection engines improves the fuel consumption as well as the exhaust emissions of such engines significantly.[1] The work presented here gives a brief overview on the basics of laser induced ignition. Flame propagation which follows a successful ignition event can be distinguished into two different regimes.[2] Combustion processes within an engine are usually quite slow - the reaction velocity is mainly determined by the heat conductivity of the combustible. Such deflagrations processes show propagation velocities well below the speed of sound. On the other hand, detonations show much higher propagation velocities. In contrast to deflagrations, detonations show propagation velocities higher than the speed of sound within the combustible. The shock front which propagates through a combustible in the case of a detonation is responsible for a considerable pressure gradient moving at supersonic velocity. Basics and possible examples of laser induced ignitions of deflagrations and detonations are given and pros and cons of laser ignition systems are discussed briefly.

Keywords: laser ignition, deflagration, q-switch, detonation, laser

1. INTRODUCTION

Combustion processes of various kinds are widely used in industrial as well as in everyday life, like combustion engines. In most cases, a well defined ignition location together with a well defined ignition time of combustion processes is of great importance. Ignition of a combustible material is usually defined as an initiation of a self-sustained reaction which propagates through the combustible material even after removing the ignition source. Conventional ignition systems, like spark plugs or heating wires are well suited but suffer from disadvantages.

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Electrode erosion, influences an the gas flow as well as restricted positioning possibilities are the main motives in search of alternatives to conventional ignition systems. Additionally, violent combustion processes can even destroy the ignition system and thus inhibit repeated ignitions.

On the other hand, it is well know that short and intensive laser pulses are able to produce an "optical breakdown" in air. Necessary intensities are in the range between $10^{10} \ldots 10^{11} W/cm^2$.[2,3] At such intensities, gas molecules are dissociated and ionized within the vicinity of the focal spot of a laser beam and a hot plasma is generated. This plasma is heated by the incoming laser beam and a strong shock wave occurs. The expanding hot plasma can be used for the ignition of a combustible material. Other laser ignition methods, like thermal ignition of a combustible due to heating of a target or resonant absorption which generates radicals are not able to fulfil the requirements on a well defined ignition location or time and will not be discussed further.

In the past, this optical breakdown has been used for ignition of gas mixtures many times.[1,2,4–7] In most cases, only slow combustion processes have been investigated. This article will present some basics of laser ignition together with results achieved by operating a laser ignition system on an internal combustion engine for a long period of time. Basics of fast combustion processes will be discussed briefly.

2. IGNITION OF COMBUSTIBLES

2.1. Spark plug ignition

Conventional ignition of a combustible requires that a high voltage is applied to the electrodes of the spark plug. The field strength reaches values of approximately $3 \cdot 10^4 V/cm$.[2,8] Electrons are accelerated by the field and hit other atoms or molecules, thus ionizing additional atoms and an avalanche-like reproduction of ionized atoms occurs and the compressed fuel/air-mixture is ignited.

For ignition of an inflammable gas mixture, the overall energy balance has to be positive within a small volume near the ignition location. Energy delivered by the spark together with the exothermal heat of reaction have to exceed energy losses caused by heat conduction and radiation losses together with the required activation energy of the molecules.

Other ignition systems, like heating wires are not as fast as required or are destroyed after one ignition sequence. Additionally, several problems occur with conventional ignition which are caused by the fact that the ignition location cannot be chosen optimally.

2.2. Laser ignition

As mentioned earlier, only laser ignition by optical breakdown fulfils the requirements on a well defined ignition location and time. A powerful short pulse laser beam is focused by a lens into a combustion chamber and near the focal spot a hot and bright plasma is generated, see fig. 1.

2.2.1. Mechanisms of laser ignition

A high voltage is applied onto the electrodes of a spark plug. The field strength reaches values in the range of approximately $3 \cdot 10^4\, V/cm$ between the electrodes of a conventional spark plug.[2,8]

In the case of a laser ignition system the laser beam is responsible for ignition of the combustible. Since the intensity of an electromagnetic wave is proportional to the square of the electric field strength $I = \sqrt{\epsilon_0/\mu_0} E^2$, ($\epsilon_0$ ... dielectric coefficient, μ_0 ... permeability of free space) one can estimate that the intensity should be in the order of $2 \cdot 10^6\, W/cm^2$, which is several orders of magnitude lower as indicated by experiments on laser ignition. One reason is that in most cases there are not enough electrons within the irradiated volume to start an avalanche electron multiplication, thus generating a hot plasma. Only at very high laser intensities a "multi photon" process where several photons hit the atom at nearly the same time[9] frees the first few electrons. Following the generation of initial electrons, a cascade ionization process generates the hot plasma finally.[10]

Such multi photon ionization processes can only happen at very high irradiation levels (in the order of $10^{10} \ldots 10^{11} W/cm^2$)[2,3] where the number of photons is extremely high. For example, nitrogen has an ionization energy of approximately 14.5 eV, whereas one photon emitted by a Nd:YAG laser has an energy of 1.1 eV, thus more than 13 photons are required for ionization of nitrogen.

(a) 1064 nm (b) 532 nm

Figure 1. Optical breakdown in air generated by a Nd:YAG laser

If electron diffusion out of the irradiated volume is neglected, the number of electrons increase exponentially during the laser pulse with the duration t

$$N = N_0 e^{t/\tau} = N_0 2^k \,, \tag{1}$$

where τ ...is the characteristic time constant of the cascade process and k is the number of generations of electrons at the end of the laser pulse. Finally, the number of electrons exceeds the breakdown threshold and a bright and hot plasma is generated. Multiplication time constant is usually quite short (approx. 1 ns).[10] Reaction velocities of combustion processes are several orders of magnitude slower. As a result, laser ignition fulfils the requirements on a well defined ignition time since there is almost no time delay between the laser pulse and the development of a hot plasma.

The required pulse energy of a laser system for ignition can be estimated by the following calculation roughly.

It is well known that the diameter d of a focused laser beam depends on the wavelength, the diameter of the unfocused beam and the focusing optics.[11]

$$d = 2 \cdot w_f = 2 \cdot M^2 \frac{2}{\pi} \frac{\lambda F}{D} \,, \tag{2}$$

where M^2 is the beam quality, F is the focal length of the optical element and D is the diameter of the laser beam with the wavelength λ. A reasonable radius w_f is in the range of approximately 100 μm and within a spherical volume $V = 4\pi w_f^3/3$ the number of molecules depend on the pressure and temperature according to the ideal gas law:

$$N = \frac{pV}{kT} \,, \tag{3}$$

with the pressure p, temperature T and Boltzmann's constant $k = 1.38 \cdot 10^{-23} J/K$.

Since not all molecules within the irradiated volume will be dissociated and ionized, one can assume that approximately 10^{13} electrons will be present at the end of the laser pulse. Dissociation and ionization requires a certain amount of energy which has to be delivered by the laser beam. First the dissociation energy W_d is required and finally $2N$ atoms are ionized (ionization energy W_i). Using known values[12] for $W_d = 9.79\,eV$ and $W_i = 14.53\,eV$ for nitrogen, the energy for dissociating and ionizing all particles inside the volume can be calculated as

$$W = N \cdot (W_d + 2W_i) \,. \tag{4}$$

For a spot radius of about 100 μm the estimation gives a required pulse energy for ionization in the order of approximately 0.1 mJ.

3. COMBUSTION

After a successful ignition event the flame propagates through the combustible. Usually, one can distinguish between different types of combustion processes.[2]

- Slow combustion processes (deflagrations): Reaction velocity is mainly determined by heat conductivity. Propagation velocity is less than the speed of sound.
- Fast combustion processes (detonations): Reaction velocity is determined by a strong shock front moving at supersonic velocity. Propagation velocity is greater than the speed of sound.

Slow combustion processes are easier to control and are not as violent as fast combustion processes. Pressure and temperature gradients inside deflagrations are always smaller and stress on components is lower, too. In the case of very high heat of reaction the relation between the temperatures which can be achieved during a deflagration and a detonation approach a threshold value greater one:

$$\frac{T_{detonation}}{T_{deflagration}} = \frac{2\gamma^2}{\gamma + 1}\,, \tag{5}$$

where $\gamma = c_p/c_v$ ... describes the adiabatic coefficient of the combustible.[13] Pressures and expansion velocities within a detonation can reach several 100 MPa and several 1000 m/s,[13,14] whereas in deflagrations pressures and expansion velocities are much lower. It is obvious that slow combustion processes are far more important than violent detonations but it is a matter of fact that some needs on a reliable ignition system for detonations exist.

4. EXPERIMENTAL

4.1. Ignition of slow combustion processes

A laser ignition system has been used for ignition of an internal combustion engine. Since results have already been published,[1,15–18] only a brief overview is given here.

Technical data of the research engine and the laser used for the experiments are summarized in table 1, the experimental setup is shown in fig. 2.

Table 1. Technical data of the research engine and the Nd:YAG laser used for the experiments.

Research engine		Q-switched Nd:YAG laser	
Number of cylinders	1	Pump source	Flash lamp
Number of valves	1	Wavelength	1064 or 532 nm
Injector	Multi-hole	Maximum pulse energy	160 mJ
Stroke	85 mm	Pulse duration	6 ns
Bore	88 mm	Power Consumption	1 kW
Displacement volume	517 cm^3	Beam diameter	6 mm
Compression ratio	11.6	Type	Quantel Brilliant

Pressure within the combustion chamber has been recorded as well as fuel consumption and exhaust gases. The laser was triggered at well defined positions of the crankshaft, just as with conventional ignition systems. Pulse energies, ignition location and fuel/air ratios have been varied during the experiments. The engine has been operated at each setting for several hours, repeatedly. All laser ignition experiments have been accompanied by conventional spark plug ignition as reference measurements.

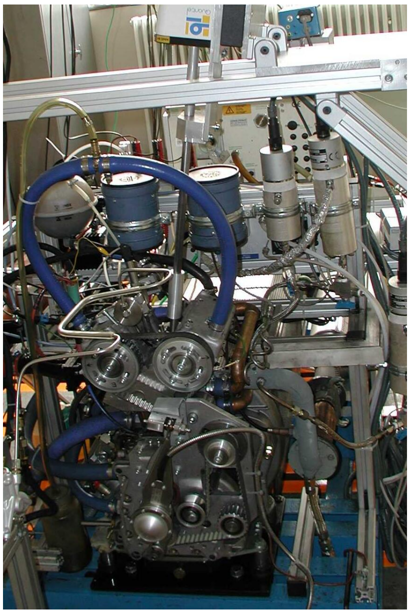
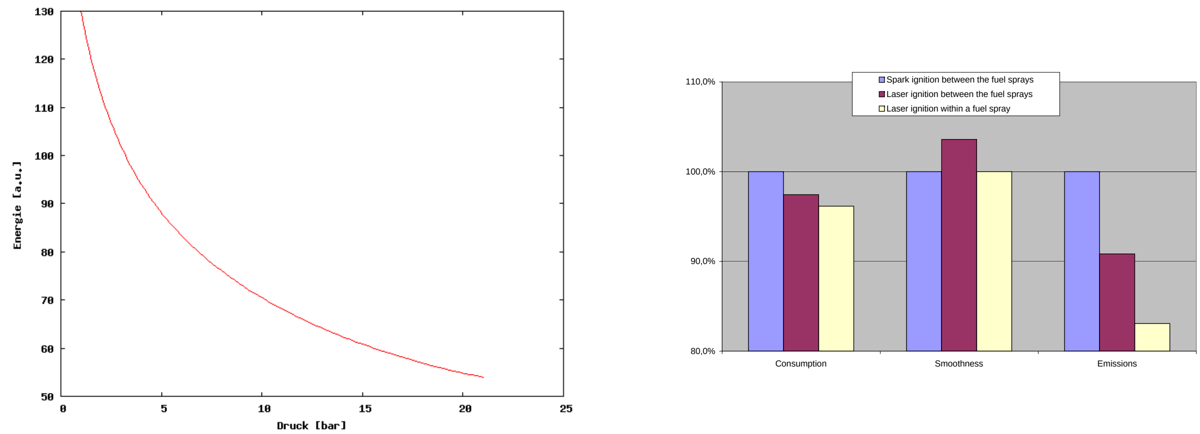


Figure 2. Research engine with the q-switched Nd:YAG laser system (top)



(a) Pressure dependence on the required pulse energy for successful ignition.

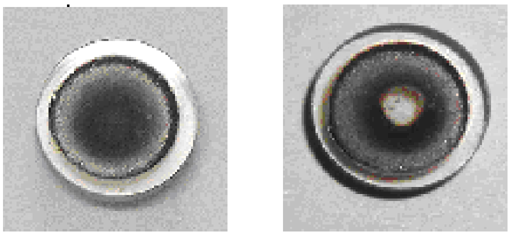
(b) Comparison between conventional spark plug ignition and laser ignition.

Figure 3. Experimental results on laser ignition of a direct injected combustion engine.

4.1.1. Results

Measurements on the dependence of the pressure on the required pulse energy for ignition are summarized in fig. 3(a). Results indicate that the required pulse energy for successful ignition decreases with increasing pressure. Results on consumption measurements are summarized in fig. 3(b). Compared to conventional spark plug ignition, laser ignition reduces the fuel consumption by several per cents. Exhaust emissions are reduced by nearly 20%. Additionally, a frequency-doubled Nd:YAG laser has been used to examine possible influences of the wavelength on the laser ignition process. No influences on the required pulse energy for successful ignition could be found.

Best results in terms of fuel consumption as well as exhaust gases have been achieved by laser ignition within the fuel spray. As already mentioned, it is not possible to use conventional spark plugs within the fuel spray



(a) After 20 h operation with spark plug ignition, heavily polluted

(b) Immediately after 100 laser pulses. Beam area is cleaned by the laser beam.

Figure 4. Beam entrance window

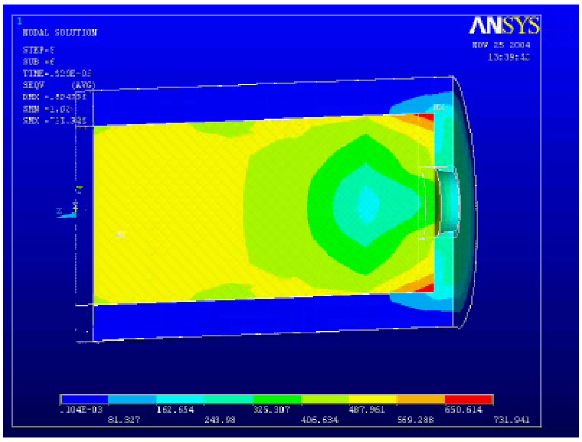


Figure 5. Equivalent vanMises stress on a beam entrance window. Maximum pressure is 500 MPa, pressure rise within 1 μs[19]

since they will be destroyed very rapidly. Laser ignition doesn't suffer from that restriction. Additionally, even with a heavily polluted beam entrance windows the direct injection engine could be operated successfully, see fig. 4.

5. SIMULATIONS

5.1. Ignition of fast combustion processes

As already mentioned, fast combustion processes (i.e. detonations) show a more violent behaviour, i.e. pressures and temperatures rise very quickly. In most cases, conventional ignition systems - like heating wires - are destroyed by the acting forces during the explosion. Nevertheless, there is a need on a reliable and repeatable ignition source which is not destroyed by the rapid combustion process. One possibility would be laser ignition but it is clear that one of the most critical points is the beam entrance window into the explosion chamber. Since pressures and temperatures can reach very high values in very short periods of time during a detonation stress on a beam entrance window is very high, too. FEM-simulations should help to clarify the question if a window can withstand the pressures during such violent combustion processes, see fig. 5. Results of the simulations indicate that a carefully designed beam entrance window will be able to withstand even pressures and temperatures caused by fast combustion processes.[19] Nevertheless, only real-world experiments can prove the validity of the FEM-simulation.

6. SUMMARY

Laser induced ignition of slow combustion processes has been examined. The feasibility of a laser-induced ignition system on a direct injected gasoline engine has been proven in long-term experiments. Main advantages are are the almost free choice of the ignition location within the combustion chamber, even inside the fuel spray. Significant reductions in fuel consumption as well as reductions of exhaust gases show the potential of the laser ignition process. Results indicate that pollution of the beam entrance window is not critical as expected, even heavily polluted windows have had no influence on the ignition characteristics of the engine. Measurements show that the required pulse energy for successful ignition decreases with increasing pressure.

Fast combustion processes (detonations) show a much more violent character than slow deflagrations. FEM-simulations indicate that a well designed beam entrance window can probably withstand pressures and temperatures during a detonation. Additional work is necessary to prove the results of the simulations by experiments.

REFERENCES

1. G. Liedl, D. Schuöcker, B. Geringer, J. Graf, D. Klawatsch, H. Lenz, W. Piock, M. Jetzinger, and P. Kapus, "Laser induced ignition of gasoline direct injection engines," in *Proc. SPIE*, **5777**, pp. 955–960, 2004. Invited paper.
2. P. D. Ronney, "Laser versus conventional ignition of flames," *Optical Engineering* **33 (2)**, pp. 510–521, 1994.
3. M.-C. Gower, "Krf laser-induced breakdown of gases," *Optics Communications* **36(1)**, pp. 43–5, 1981.
4. J. Syage, E. Fournier, R. Rianda, and R. Cohn, "Dynamics of flame propagation using laser-induced spark initiation: Ignition energy measurements," *Journal of Applied Physics* **64 (3)**, pp. 1499–1507, 1988.
5. M. Lavid, A. Poulos, and S. Gulati, "Infrared multiphoton ignition and combustion enhancement of natural gas," in *SPIE Proc.: Laser Applications in Combustion and Combustion Diagnostics*, **1862**, pp. 33–44, 1993.
6. J. Ma, D. Alexander, and D. Poulain, "Laser spark ignition and combustion characteristics of methane-air mixtures," *Combustion and Flame* **112 (4)**, pp. 492–506, 1998.
7. R. Hill, "Ignition-delay times in laser initiated combustion," *Applied Optics.* **20 (13)**, pp. 2239–2242, 1981.
8. Bergmann and Schaefer, *Lehrbuch der Experimentalphysik: Elektrizität und Magnetismus*, vol. 2, Walter de Gruyter Berlin, 1981.
9. T. Huges, *Plasma and laser light*, Adam Hilger, Bristol, 1975.
10. C. DeMichelis, "Laser induced gas breakdown: A bibliographical review," *IEEE Journal of Quantum Electronics* **5(4)**, pp. 188–202, 1969.
11. W. Koechner, *Solid-State Laser Engineering*, vol. 1, Springer, 1999.
12. D. R. Lidde, ed., *CRC Handbook of Chemistry and Physics*, CRC Press, 2000.
13. L. D. Landau and E. Lifschitz, *Hydrodynamik*, vol. 6 of *Lehrbuch der theoretischen Physik*, Harri Deutsch, Lehrbuch der theoretischen Physik ed., 1991.
14. G. Ben-Dor, O. Igra, and T. Elperin, eds., *Handbook of Shock Waves: Theoretical, Experimental and Numerical Techniques*, vol. 1, Academic Press, 2001.
15. B. Geringer, J. Graf, D. Klawatsch, H. P. Lenz, G. Liedl, D. Schuöcker, W. F. Piock, M. Jetzinger, and P. Kapus, "Laserinduzierte Zündung an einem Otto-DI-Brennverfahren der zweiten Generation," in *Fortschritt-Berichte VDI 24. Internationales Wiener Motorensymposium, 15.-16. Mai 2003, 2* **12**(539), pp. 87–109, VDI Verlag Düsseldorf, 2003.
16. B. Geringer, J. Graf, D. Klawatsch, H. Lenz, G. Liedl, D. Schuöcker, W. Piock, M. Jetzinger, and P. Kapus, "Laserzündung - ein neuer Weg für den Ottomotor?," *MTZ - Motortechnische Zeitschrift* **3**, pp. 214–219, 2004.
17. B. Geringer, J. Graf, D. Klawatsch, H. Lenz, G. Liedl, D. Schuöcker, W. Piock, M. Jetzinger, and P. Kapus, "Laserinduzierte Zündung an einem Otto-DI-Brennverfahren der zweiten Generation," in *24. Internationales Wiener Motorensymposium*, H.-P. Lenz, ed., pp. 87 – 109, VDI Verlag GmbH, Düsseldorf, 15.- 16. Mai 2003.
18. M. Jetzinger, *Unkonventionelle Zündsysteme und Laserzündung bei Ottomotoren.* PhD thesis, TU Wien, 2002.
19. R. Bielak, "Fe-simulations of detonations." priv.Comm., 2005.