LASER FIRED LOW EMISSION FUTURISTIC INTERNAL COMBUSTION ENGINES

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Internal combustion engine play a dominant role in transportation and energy production. As a matter of fact, excellent efficiencies of internal combustion engines -in the first place of gas engines -of presently close to 46% are only achievable if highest mean pressures are applied. This requires remarkable technical improvements in general, and especially with respect to the ignition system employed. With conventional spark ignition, a limit around 2.5 MPa is observed [1]. It is impossible in practical operation to raise the spark voltage beyond 35 kV, and this is associated with a considerable reduction of lifetime.

Advancing the state of art of ignition systems for internal combustion engines is crucial to meet increased performance requirements. Severely reduced spark plug performance and durability is an unfortunate consequence as engines are simultaneously being pushed to higher power densities and leaner stoichiometry in order to improve efficiency and lower emissions. To compensate power density losses due to leaner operation, high pressure of initial charge is used to increase in-cylinder pressure at the time of combustion. However, an important parameter is the ignition under extreme conditions, lean combustible mixture and high initial pressure, requiring high voltage when using conventional spark plug technology. Providing the necessary spark energy to operate these engines significantly reduces the lifetime of spark plugs.

Several concepts for alternative ignition systems are under development or consideration: plasma ignition, high frequency ignition, Diesel micro pilot ignition, auto ignition concepts like HCCI (homogeneous charge compression ignition), shock wave concepts for ignition, and laser ignition. In the case of diesel pilot ignition, a small diesel jet is introduced into the compressed gas mixture at proper timing which auto ignites due to the advanced pressure and temperature environment. As a consequence, this pilot flame leads to combustion of the mean gas fuel. Another way is to use the discharge between two or more electrodes of a spark plug. Such a breakdown could be achieved by a DC as well as by an AC electrical field.

Laser is an alternative ignition source for engines. Short laser pulses of several nanoseconds of duration, delivered by a Q-switched laser, are focused by a proper lens system inside the combustible mixture. If the peak intensity in the focal region overcomes certain threshold intensity, breakdown occur leading to formation of a plasma spark whose size depends on the numerical aperture (NA) of the focused beam as shown in figure 1. If the energy content of the spark is high enough, the

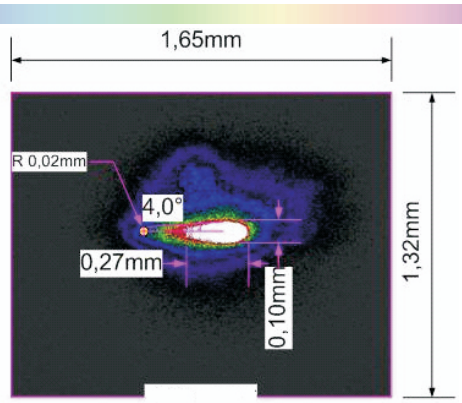

Figure 1. Emission of the laser plasma 30 ns after the laser pulse of 20 mJ pulse energy, laser beam entering from right to left [2].

mixture becomes ignited. Laser ignition can be divided into two main parts. The first one is the spark creation due to the local deposition of energy. This can be achieved in any gas. Breakdown is associated with plasma formation and shock wave generation. The second part is the ignition itself based on a positive balance between the deposited energy and the losses. In this case, a flame kernel can develop.

years because of its many potential benefits over conventional ignition system. The main advantages of laser ignition are:

- arbitrary positioning of the ignition plasma in the combustion chamber
- absence of quenching effects by the spark plug electrodes, which allows ignition of leaner mixtures and consequently lower NO_x emissions
- because of absence of erosion effects as with the spark plug, the lifetime of a laser-ignition system is significantly longer precise ignition timing
- simpler regulation of the ignition energy deposited in the ignition plasma easy possibility of multipoint ignition to speed up the low combustion speed of lean mixtures

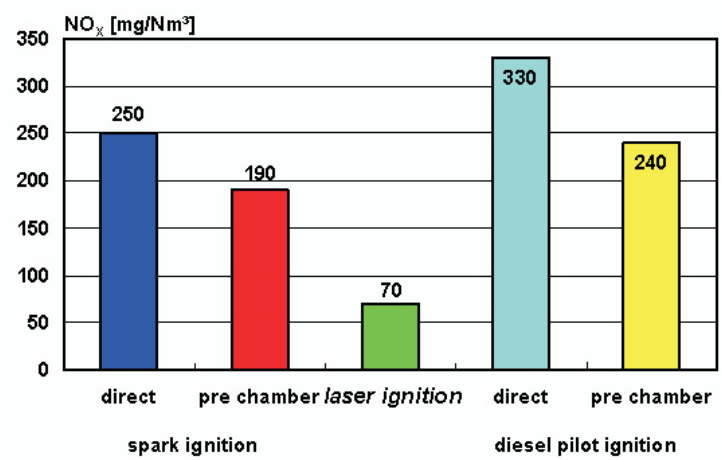

Figure 2. NO_x emission of a gas engine operated according to 5 different concepts (first generation of laser ignition engine tests at GE Jenbacher) [4]

In 1978 J.D. Dale [3] first demonstrated laser ignition for combustion initiation of internal combustion engines. The basic concept of laser ignition is to use a laser beam (as opposed to a conventional electrical spark plug) to produce a combustion initiating spark. By focusing the beam from a pulsed laser to a sufficiently high intensity (small beam dimension) a combustion initiating spark may be produced. Since the initial demonstrations by Dale et al, subsequent investigations have demonstrated the potential benefits of laser ignition when applied to engines.

Interest in laser ignition has increased in recent

The possibility of choosing the location of the focal point in the cylinder is a significant advantage for the combustion process. It is

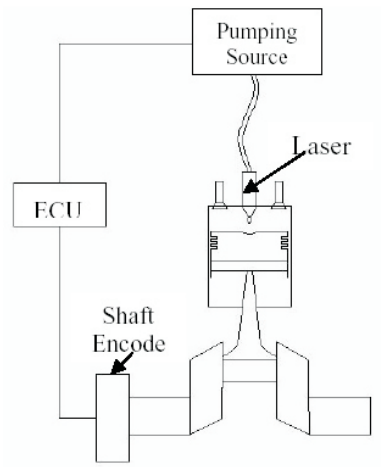

Figure 3. Schematic diagram of laser per cylinder system

possible to position the plasma exactly in the middle of the cylinder. High load / ignition pressure of the gas engine for optimum efficiency demands increasing spark plug voltage leading to enhanced erosion of the

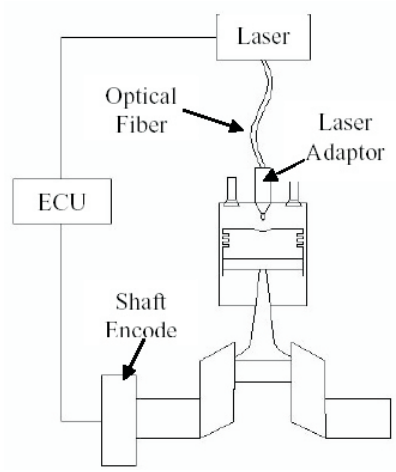

Figure 4. Schematic diagram of one laser for all cylinder system

electrodes. Therefore, it is a main aim to increase the lifetime of an ignition system and minimize the service efforts. A diode-pumped laser ignition system has potential lifetime up to 10,000 hours compared to spark plug lifetimes of the order of 2000 to 4000 hours [source GE Jenbacher, Austria]. The efficiency of a diode-pumped laser is approximately 10 %. Furthermore, with the possibility of multipoint ignition, the combustion can be started with two or more plasmas at different points but at the same time in the cylinder which again shortens the total combustion duration significantly.

A major reason to prefer laser ignition in comparison to conventional spark plug ignition is the feasibility of a leaner limit for ignition together with higher ignition pressures leading to higher efficiency and much lower NOx and CO emissions in gas engines.

Different concepts for the laser arrangement with respect to the engine have been pursued: e.g. the direct mounting of a miniature laser on every cylinder shown in figure 3 or the remote positioning of one or several lasers and the transfer of the pulses to the input window as shown in figure 4.

The latter can only be imagined under practical circumstances to be carried out via optical fibers. However, it is not an easy task to propagate MW pulses through monomode fibers; in case of multimode propagation the favourable beam properties would be lost and no small focal diameters going along with lowest pulse energies could be achieved any more. The only viable solution may be represented by hollow core photonic crystal fibers. Experiments based on the evacuation of the core showed that mono-mode transportation of ns- pulses with peak intensity orders of magnitude beyond the breakdown limit of silica is feasible [5]. Presently, direct laser mounting on the cylinder of a highly compact and robust solid-state laser is considered be the most favorable solution.

What are the predicted problems of laser ignition? One of the most serious obstacles of laser ignition is to develop a compact and robust laser system delivering laser pulses of high spatial coherence and sufficient energy for reliable ignition in all permissible modes of engine operation. Such requirements can only be fulfilled by solid-state lasers. Since the durability of the ignition system is one major requirement, long lasting laser diodes have to be used as a pump source for the ignition laser. The system must be highly resistant against mechanical vibrations and thermal load if directly mounted on the cylinder head. Due to the hot vicinity of the cylinder, sufficient cooling of the high power laser system being of low overall efficiency (10 % maximum) might become a serious problem.

Another critical point is the durability of the chamber window enabling to transmit the laser beam into the cylinder. Would it be possible to

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