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Effect of compression ratio on combustion, performance and emissions of a laser ignited single cylinder hydrogen engine

*Anuj Pal, Avinash Kumar Agarwal**

Engine Research Laboratory, Department of Mechanical Engineering, Indian Institute of Technology Kanpur, Kanpur 208016, India

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A B S T R A C T

Energy demand and emission norms are forcing automotive researchers to explore superior fuels and develop new combustion technologies to comply with stringent emission norms being adopted worldwide and continue the quest for improving engine performance. Laser ignition is one such technology, which has potential to improve the engine performance and reduce emissions from the internal combustion (IC) engines. To reduce emissions and counter depletion of fossil fuels, use of hydrogen as an alternate fuel in engine is gaining momentum worldwide. Laser ignition of hydrogen–air mixtures has exhibited promising results in preliminary experimental investigations. In this follow-up research to develop a laser ignited prototype hydrogen engine, a diesel engine was modified to operate on hydrogen. Port-fuel injection of hydrogen was done in this prototype engine and the engine was installed with prototype laser ignition system. Apart from proven advantages of laser ignition, one main reason for implementing this technology was to eliminate the spark plug electrodes of conventional ignition system, which act as a source of pre-ignition inside the combustion chamber, when they get heated at higher compression ratios. The study was aimed to explore the effect of compression ratio on laser ignited IC engine because hydrogen has considerably higher octane number and it would be worthwhile to make use of higher compression ratios for improving engine performance and emission characteristics. Three compression ratios i.e. 10, 11 and 12 were used to find the effect of compression ratio on engine combustion, performance and emission characteristics of the laser ignited hydrogen fueled prototype engine.

Introduction

Laser ignition has emerged as a promising technology to fulfill the requirements of superior combustion performance and emission characteristics. Laser ignition is considered as a next generation and advanced ignition technique for igniting combustible mixtures of various fuels. Transportation sector globally is dependent on fossil fuels, and the fossil fuel reserves are getting depleted quickly due to very high energy

* *Corresponding author*. Tel.: +91 512 2597982; fax: +91 512 2597408.
E-mail address: akag@iitk.ac.in (A.K. Agarwal).
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demand. Increase in demand for fossil fuel and stringent emission norms are forcing researchers to explore use of hydrogen as an alternative fuel.

In laser ignition, a pulsed laser beam is focused inside the combustion chamber very tightly on a small focal volume. When the energy density at this focal point increases above a certain threshold value, plasma is generated, which initiates combustion of fuel–air mixture. For laser ignition, short laser pulses of few nanoseconds pulse width are used, which can be generated by a Q-switched laser. There are various processes involved in laser ignition [1]. Through a laser pulse, plasma is created, which leads to formation of a shock waves. This shock wave helps in flame kernel propagation, ultimately leading to combustion initiation in the combustible fuel–air mixture. Laser pulse duration is of the order of few nanoseconds only. Ignition delay of various fuels is in the range of few nanoseconds to 100 ms, depending upon the fuel–air mixture strength. Combustion duration depends on several parameters such as in-cylinder pressure, temperature, laser energy, plasma position etc.

There are several advantages of laser ignition over conventional spark ignition [2]. With laser ignition, more precise ignition timings can be achieved. Plasma position can be changed in the combustion chamber, which is not possible in case of conventional spark ignition. This helps in optimizing combustion of fuel–air mixture in the chamber by reducing the maximum flame travel distance. Multi-point ignition is also possible with laser ignition, leading to faster combustion. Laser plasma has relatively higher energy density and temperature, therefore combustion of relatively leaner fuel–air mixtures can be achieved easily. Energy density of plasma can be increased by increasing the energy of the laser pulse, therefore lean combustive limits of fuel–air mixtures can be further extended. One of the major issue which hydrogen fueled engines faces is the problem of pre-ignition/backfire, which happens due to hot spots inside the combustion chamber. These hot-spot inside the combustion chamber could be heated spark plug electrodes, sharp valve edges, carbonaceous deposits primarily formed by lubricating oil additive remnants etc. however the heated spark plug electrodes are the main source of pre-ignition therefore, if the spark plug electrodes are removed from the engine combustion chamber, chances of pre-ignition/backfire reduce drastically. Laser ignition is an electrode-free ignition, which can reduce pre-ignition or backfire in a hydrogen fueled engine.

For installing a laser ignition system in the engine, several hardware modifications are required to be done. One of the main challenges is to be able to pass the laser beam into the combustion chamber. Bihari et al. discussed two approaches to develop laser ignition system for a stationary engine [3]. First one was using one laser per cylinder. In this approach, a laser source is mounted on each cylinder to create spark inside the cylinder. This technology suffers from the issues of high system cost, and laser durability due to engine vibrations and heat dissipation. Second one was using single laser source to cater to all cylinders. In this case, the laser beam was propagated into the cylinders using optical fibers. Passing laser beam through optical fibers gives rise to issue of maintaining high beam quality. Several researches are involved in designing better optical fibers, which can transmit pulsed laser for laser ignition without affecting the beam quality adversely.

Hydrogen has shown great promise as future alternate fuel for automotive applications. It is a non-toxic substance, therefore would not create harmful effects in the environment, if released by accident. It has very high calorific value, therefore produces higher heat release per unit mass upon combustion. Hydrogen is completely free from carbon, thus its combustion does not produce any greenhouse gas (GHG) emissions. Hydrogen can be relatively easily ignited therefore leaner fuel–air mixtures can be burned thereby improving fuel economy in idling or lower engine load conditions. It has very high diffusivity therefore it generates more homogeneous mixture rather quickly. In case of an accidental release into the environment, it would move upwards quickly (because of lower density) and would form very lean homogeneous mixture outside the combustible limits, thus preventing catastrophic disaster. Also its octane rating is excellent, enabling it to be used in engines with higher compression ratios without any fear of knocking.

Several experimental studies have been carried out to understand combustion and emission characteristics of hydrogen fueled engine. Hydrogen's direct injection in IC engine was investigated by Zhenzhong et al. [4]. They investigated optimum injection and ignition timings. For a fixed engine speed and a fixed start of injection (SOI) of 6° Before Top Dead center (BTDC) without changing the fuel injection quantity, engine combustion was greatly affected by varying ignition timings. Mathur et al. [5] performed timed manifold injection (TMI) to study hydrogen combustion characteristics. Compression ratio and engine speed were varied during these experiments. Indicated Mean Effective Pressure (IMEP) increased with increasing compression ratio and also with increasing equivalence ratio at a fixed compression ratio. At high engine speeds, exhaust gas temperature increased to a maximum of 520 °C with TMI.

Researchers also investigated the advantages of laser ignition over conventional ignition systems. Several researchers performed laser ignition experiments in a constant volume combustion chamber (CVCC) by simulating conditions similar to end of the compression stroke conditions of an engine combustion chamber, in order to carry out fundamental combustion investigations. Srivastava et al. [6] performed experiments in a CVCC filled with hydrogen–air mixtures using a Q-switched Nd:YAG laser. Initial chamber conditions were 3 MPa pressure and 373 K temperature. They reported higher peak pressure rise inside the CVCC with laser ignition compared to spark ignition. Weinrotter et al. [1] performed comparative study of laser ignition and conventional spark ignition of methane–air mixture in a CVCC. All experiments were performed at initial chamber temperature of 473 K. Laser ignition extended the lean limit from $\lambda = 1.65$ to $\lambda = 2.0$ at low chamber filling pressure. Ignition delay was also relatively shorter for laser ignition. Excess chamber pressure decreased with increasing λ for both laser ignition and spark ignition. Xu et al. [7] investigated combustion of gasoline–air mixture in a CVCC using Q-switched Nd:YAG laser beam at two different wavelengths (532 nm and 1064 nm). They studied the ignition probability and minimum ignition energy (MIE) required for laser ignition and compared their results