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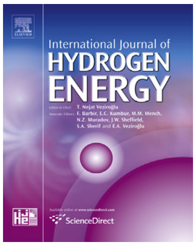

Comparative study of laser ignition and conventional electrical spark ignition systems in a hydrogen fuelled engine

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ABSTRACT

Increasing population and demand for fossil fuels is leading to rapid depletion of petroleum reserves. Hydrogen has great promise as an alternative fuel for powering next generation internal combustion engines with improved thermal efficiency and reduced emissions. Laser ignition (LI) has emerged as an efficient ignition technique for delivering superior engine efficiency with lower emissions. Use of LI to initiate combustion in an engine fuelled with hydrogen–air mixtures can greatly help in reducing emissions, improving engine performance and tackling the problem of fossil fuel depletion. In this study, a laser ignited hydrogen fuel prototype engine has been developed and comparison of its performance, emissions and combustion parameters is done with baseline data generated using conventional spark ignition (SI) system.

Introduction

In the second half of twentieth century, global population began to explode. This led to phenomenal increase in demand for conventional fossil fuels to sustain increased transportation demand of a modern society. By 2030, global population will be 8 billion [1] and its primary energy demand will cross 700 EJ/year [2]. The fossil fuel reserves are rather limited, therefore more demand for fuel will straightway translate into higher energy prices, which will lead to fuel prices led inflation world over. In addition, world is facing serious challenges such as environmental degradation and climate change, which are reportedly because of pollution and harmful emissions caused by petroleum fuelled vehicles. In order to control and arrest this environmental damage, stringent emission norms have been adopted worldwide which are becoming more and more stringent with time. Therefore to avoid the rapid depletion of fuel reserves, slow down the increase in fuel prices and for stringent emission norm compliance, researchers are exploring alternate fuel options for vehicles. These alternate fuels can be adopted in current generation engines with minimal hardware modifications. Several alternative fuel candidates such as biodiesel, compressed natural gas (CNG), ethanol, hydrogen, hydrogen-CNG mixtures (HCNG), straight vegetable oils (SVO), liquefied petroleum gas

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(LPG) have been investigated for their engine performance in order to assess their technical feasibility in current generation engines. In a quest of running the internal combustion engines with improved thermal efficiency and lower emissions, hydrogen has emerged as a prominent alternate fuel candidate with ultra-low emission potential due to its extremely clean emission spectra.

Compared to other fuels such as gasoline, diesel, compressed natural gas (CNG), biodiesel etc., hydrogen offers numerous advantages as an alternate transportation fuel such as it can be produced using various renewable primary energy sources from water (through electrolysis), from coal and biomass (through gasification), from natural gas (using steam methane reforming and other ways) [3]. It does not contain carbon, hence does not emit any greenhouse gas upon combustion. Hydrogen has higher calorific value (w/w) resulting in higher power output upon combustion, higher auto-ignition temperature, low ignition energy, higher diffusivity and higher flame propagation speed compared to gasoline. In addition to several advantages, hydrogen has few disadvantages and limitations also. Due to very small ignition energy required to initiate combustion, chances of backfire and pre-ignition is higher in hydrogen fuelled engines. Density of hydrogen is very low, therefore significantly larger volume of hydrogen is required compared to conventional fuels for the same range of the vehicle. Among these, pre-ignition and backfire remain the biggest challenges for commercialization of hydrogen engine. Researchers have used several induction techniques, injection strategies, and water induction in the intake manifold for hydrogen fuelled engine in order to eliminate/control engine backfire. For controlling NO_x emissions, EGR and/or water injection into the intake manifold have been successfully attempted.

Das and Mathur [4] controlled NO_x emissions from a hydrogen fuelled engine using different EGR rates. Experiments were performed on a carbureted hydrogen engine. They obtained significant reduction in NO_x emissions using 15% EGR. Improvement in fuel consumption was also achieved. Brake specific fuel consumption (BSFC) decreased upon increasing EGR. Increasing the spark advance increased the temperature inside the combustion chamber, which increased the NO_x emissions from the engine. Mohammadi et al. [5] investigated performance and NO_x emissions by direct injection of hydrogen in a single cylinder SI engine and varied injection timings and ignition timings. Maximum BMEP of 6.5 bars was obtained, when hydrogen was injected into the combustion chamber during the intake stroke (300° BTDC). For this case, maximum brake thermal efficiency was found to be 35% at $\Phi = 0.5$. At $\Phi = 0.7$, NO_x emissions were roughly 8000 ppm. Injecting hydrogen during early stages of compression stroke (140° BTDC) increased BMEP to 9.7 bars with brake thermal efficiency of 38.9%. This led to reduction in NO_x emissions due to lean engine operation. Varde and Frame [6] performed experiments in a single cylinder SI engine to quantify the advantages of port injection of hydrogen over carbureted induction in terms of backfire and cyclic variations. Experiments were performed at 1800 rpm and 2100 rpm engine speeds. Improvements in lean-burn limit were observed for the port injection system. Thermal efficiency of port injection system in lean region was also higher. Maximum NO_x emissions were observed with mixture strength slightly leaner then stoichiometric. Flame speed for port injection was found to be higher than carburetion engine. At 20° BTDC, backfire occurred between $\Phi = 0.9$ to 1.15 for carburetor, whereas for port injection, backfire occurred between $\Phi = 1.1$ to nearly stoichiometric mixtures.

Another technique to overcome auto-ignition and backfire from hydrogen fuelled engine is by using electrode-less ignition system such as laser ignition (LI). In LI, a pulsating laser beam is converged at a point using a converging lens, which creates plasma at the focal point of the converging lens. Plasma is formed, when the energy density at the focal point increases beyond a threshold value. Apart from controlling backfire and auto-ignition, LI has proved to be a better ignition technique for improving engine performance and emissions. LI was successfully performed for the first time in an IC engine in 1978 by Dale et al. [7]. They compared the results of LI with baseline conventional spark plug ignition system and reported that at 300 mJ/pulse laser energy, peak cylinder pressure rise was higher for LI. Minimum air-fuel ratio limit, at which LI was possible, reduced to 27.8:1 compared to 22.5:1 for conventional ignition system. At a particular engine operating condition, 17% improvement in BSFC was observed, while using 17% EGR. Herdin et al. [8] performed experiments in a large-bore engine fuelled with natural gas. They reported that increasing the in–cylinder pressure decreased the energy required for creating plasma inside the combustion chamber. Compared to conventional spark plug ignition system, ignition delay was shorter for LI. Liedel et al. [9] investigated LI using a Q-switched Nd: YAG laser with wavelengths of 1064 nm and 532 nm and a pulse duration of 6 ns in a GDI engine. Fuel consumption in LI system was significantly lower compared to the conventional ignition system. Exhaust emissions reduced by 20% for LI. By changing the wavelength of the laser, no significant effect on engine performance was observed.

Both McMillian et al. [10] and Srivastava and Agarwal [11] performed experiments using SI and LI system in a natural gas fuelled single cylinder engine. MacMillian et al. [10] performed experiments to determine misfire limit and knock limit of LI system. They reported increased misfire limit, and decreased ignition delay for LI compared to SI. Srivastava and Agarwal [11] carried out a comparative study between LI and SI. They also varied laser plasma position to further investigate the effect of plasma position on the engine performance. Superior combustion and performance parameters were obtained for LI compared to SI. Also slight increase in BSFC and power output was obtained upon moving plasma position deeper inside the constant volume combustion chamber (CVCC).

Experiments on LI of hydrogen–air mixture were performed by Srivastava et al. [12] however in a CVCC. A Q-switched Nd:YAG laser was used for the experiments. Pressure-time curves were obtained for both LI and SI by varying air-fuel ratio, while maintaining constant initial chamber filling pressure and initial chamber temperature. Variations in minimum laser pulse energy required to initiate combustion were determined by varying initial chamber filling pressure and air-fuel ratio. It emerged that peak pressure in both cases i.e. LI and SI was comparable but pressure