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Effect of laser pulse energy on laser ignition of port fuel injected hydrogen engine

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ABSTRACT

For improving engine performance and emissions, researchers are improving combustion; and developing sustainable fuels in order to ensure global energy security. In this experimental investigation, a prototype hydrogen fuelled engine using port fuel injection was developed. A newly developed laser ignition system was installed in the test engine. Laser ignition system offers several advantages over the conventional electrical spark ignition systems such as flexibility of locating the plasma, capability to ignite leaner mixtures and significantly lower NOx emissions. In order to develop a practical laser ignition system, it is important to reduce the laser pulse energy and optimise it for best engine performance. A Q-switched Nd:YAG laser (1064 nm wavelength) with pulse duration of 6–9 ns was used for laser ignition of hydrogen–air mixture in the engine. Two laser pulse energies (16.6 mJ/pulse and 12.1 mJ/pulse) were used for the experiments and the effect of varying laser pulse energy on combustion, performance and emissions characteristics of the laser ignited hydrogen fuelled engine was evaluated experimentally.

Introduction

Demand for conventional fuels is increasing rapidly due to global population explosion, urbanization and motorization [1]. Fossil fuels have limited reserves, therefore they are depleting at a fast pace. Since conventional fuels contain carbon, their combustion leads to emission of greenhouse gases in addition to other hazardous gases. Stringent emission norms are being adopted worldwide to combat the pollution from vehicles. In order to address this, researchers are exploring alternative fuels, which are sustainable, less polluting and environment friendly.

Hydrogen is one such alternate fuel for vehicles, which has immense potential because it does not emit GHG after combustion. There are numerous other advantages of using hydrogen as an IC engine fuel. However for making an IC engine compatible with hydrogen, several hardware modifications are required. Hydrogen can be generated from a variety of renewable resources such as water, coal, biomass, and natural gas, using a host of production processes. Upon combustion, hydrogen emits water vapors. Hydrogen has higher diffusivity in air compared to any other gaseous fuel therefore in case of an accident, it quickly disperses upward, thus lowering the possibility of a catastrophic accident significantly. Hydrogen is colorless, odorless, non-toxic gas

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therefore it does not have any serious environmental implication, if released into atmosphere in case of an accident. Due to hydrogen's higher diffusivity, it quickly forms homogeneous mixture in the engine combustion chamber. Minimum ignition energy for fuels like Methane, Butane, Propane, Gasoline and Hydrogen are 0.29 mJ, 0.25 mJ, 0.26 mJ, 0.8 mJ, 0.02 mJ respectively. Due to hydrogen's low ignition energy requirement for initiating combustion, even very lean hydrogen–air mixture can be ignited easily in an IC engine. Although this reduces specific fuel consumption at lower loads but it also increases the possibility of uncontrolled combustion.

Apart from these favorable fuel properties, hydrogen has some peculiar properties, which make it challenging to handle and use it as an IC engine fuel. Hydrogen has very small flame quenching distance [2–4], therefore there is a strong possibility of hydrogen flames propagating backwards into the intake manifold through the inlet valve gap, which can potentially cause backfire. Hydrogen has very low density [2–4], therefore for obtaining high engine power output, large volume of hydrogen is required to be inducted into the engine combustion chamber compared to any other conventional fuel, which reduces the volumetric efficiency of the engine. For adequate vehicle range, large hydrogen storage is essential. This poses a significant challenge for its utilization as an alternate fuel, especially in light-duty vehicles because of lack of storage space. Because of its low ignition energy requirement, chances of pre-ignition and backfire are significantly higher in hydrogen compared to other conventional fuels. Pre-ignition and backfire in a hydrogen fuelled engine remain the biggest challenges, prohibiting its commercialization. These can be resolved by developing electrode-less ignition system and use of laser ignition system for igniting hydrogen–air mixtures in an IC engine is one such possible solution. Laser ignition has emerged as a promising technology for improving the engine performance using gaseous alternate fuels.

In laser ignition, a short pulsating laser beam is focused at the focal point using a converging lens, which creates high intensity plasma at the focal point. Plasma is formed only when the energy density at the focal point breaches the threshold for plasma generation. For laser ignition of an IC engine, short laser pulses of few nanoseconds are used, which can be generated by a Q-switched laser.

Most research studies related to laser ignition of hydrogen–air mixtures are conducted in a constant volume combustion chamber (CVCC). Dharamshi et al. [5,6] performed several experiments of laser ignition of hydrogen–air mixtures in a CVCC. They varied relative air–fuel ratio (λ) and laser pulse energy [5]. Upon increasing λ, reduction in peak pressure rise (P_{max}) and rate of pressure rise (RoPR) in the combustion chamber were observed. Heat release rate (HRR) and flame speed decreased with increasing λ. Upon increasing laser pulse energy, time required to attain P_{max} decreased, which indicated relatively higher flame speed for laser pulse with higher energy. Experiments were conducted by varying initial CVCC filling pressure and temperature, focal length of the converging lens and the plasma position [6]. Minimum pulse energy (MPE) required to initiate combustion decreased for higher CVCC temperatures. MPE decreased for shorter focal length of the converging lens and combustion duration decreased by moving the plasma position towards the center of the CVCC [6].

Several researchers used laser ignition for igniting IC engines fuelled with gasoline and compressed natural gas (CNG). Laser ignition of IC engine was successfully demonstrated first by Dale et al., in 1978 [7]. They reported higher peak cylinder pressure with laser ignition compared to conventional spark ignition. With laser ignition, relatively leaner fuel–air mixtures could be ignited in the engine combustion chamber. Bihari et al. [8] compared laser ignition with conventional electrical spark ignition in a single cylinder engine fuelled with CNG. They used a frequency doubled Nd:YAG laser (532 nm) for these experiments. They reported that lean-burn limit extended from an equivalence ratio of 0.55–0.5 with laser ignition. NOx emissions reduced by 50% in case of laser ignition. For laser ignition, coefficient of variation of indicated mean effective pressure (COV_{IMEP}) was 5.2% at an equivalence ratio (φ) of 0.52, while for conventional ignition, COV_{IMEP} was 16.5% at φ of 0.55. Mullett et al. [9] investigated laser ignition in a gasoline engine using a Q-switched Nd:YAG laser (1064 nm). Effects of beam quality, pulse energy, minimum beam waist size and focal length of the converging lens on the engine performance, combustion and combustion stability were investigated. They reported that by increasing the aperture diameter of the laser head and the focal length of the converging lens, minimum ignition energy required increased. Greater combustion stability was observed with laser ignition compared to conventional spark ignition.

Prior to the present investigations, authors carried out an experimental study comparing a laser ignition system and a conventional electric spark ignition system [10]. The previous studies concluded that laser ignition was superior compared to conventional electric spark ignition in terms of overall engine performance. Engine combustion was superior with laser ignition, leading to higher P_{max} and HRR. It also led to higher brake thermal efficiency (BTE) and lower NO emissions from the engine compared to conventional electrical spark ignition system. It is well known that with laser ignition system, several parameters can be varied, which may lead to improved engine performance. In order to further explore the advantages of laser ignition system, laser pulse energy was varied in this investigation in order to look for its effect on engine performance. In this study, laser ignition of hydrogen–air mixture was achieved in a prototype hydrogen fuelled engine and the laser pulse energy was varied to assess its effect on engine combustion, performance and emission characteristics. For this investigation, two different laser pulse energies were used.

Experimental setup

A naturally aspirated diesel engine (Kirloskar, DM10; bore 102 mm and stroke 116 mm) was modified and converted into a prototype port-fuel injected (PFI) spark ignition (SI) engine, which was capable of operating on gaseous fuels. For loading this engine, and for torque and speed measurements, a DC dynamometer (Dynomerk; DC-35) was coupled to the engine. Hydrogen engine has possibility of backfire in the intake manifold, which can potentially lead to a catastrophic