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Article *in* International Journal of Hydrogen Energy · December 2015

DOI: 10.1016/j.ijhydene.2015.10.012

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INTERNATIONAL JOURNAL OF HYDROGEN ENERGY 41 (2016) 675–682

Available online at www.sciencedirect.com

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journal homepage: www.elsevier.com/locate/he

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ARTICLE INFO

Article history:
Received 7 July 2015
Received in revised form
5 October 2015
Accepted 5 October 2015
Available online 1 December 2015

Keywords:
Laser ignition
Laser pulse energy
Hydrogen
Port fuel injection
Combustion characteristics

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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http://dx.doi.org/10.1016/j.ijhydene.2015.10.012

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

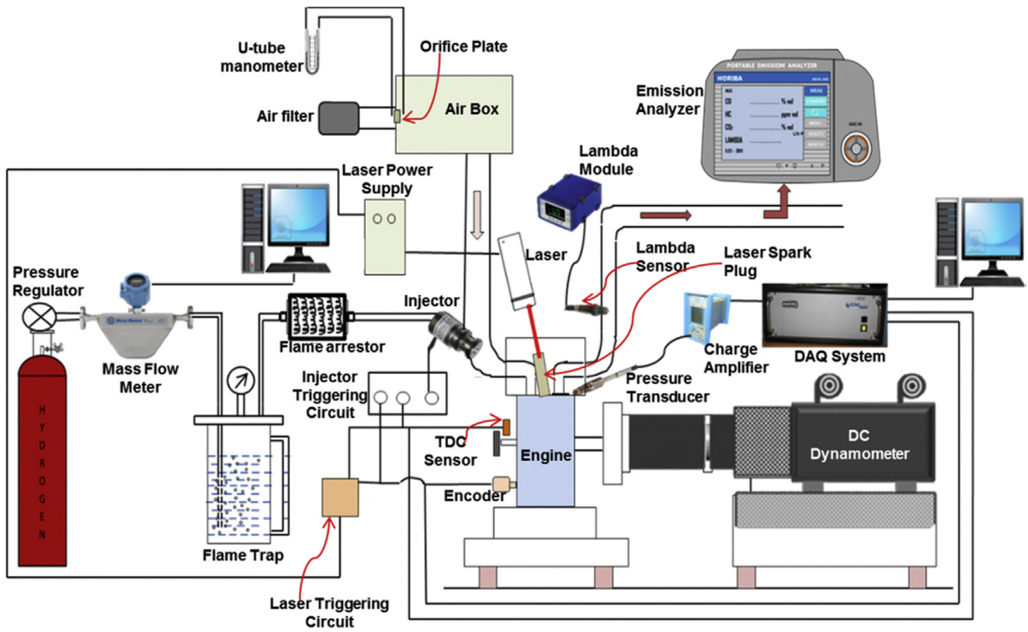

Fig. 1 – Schematic of the experimental setup for laser ignition of hydrogen.

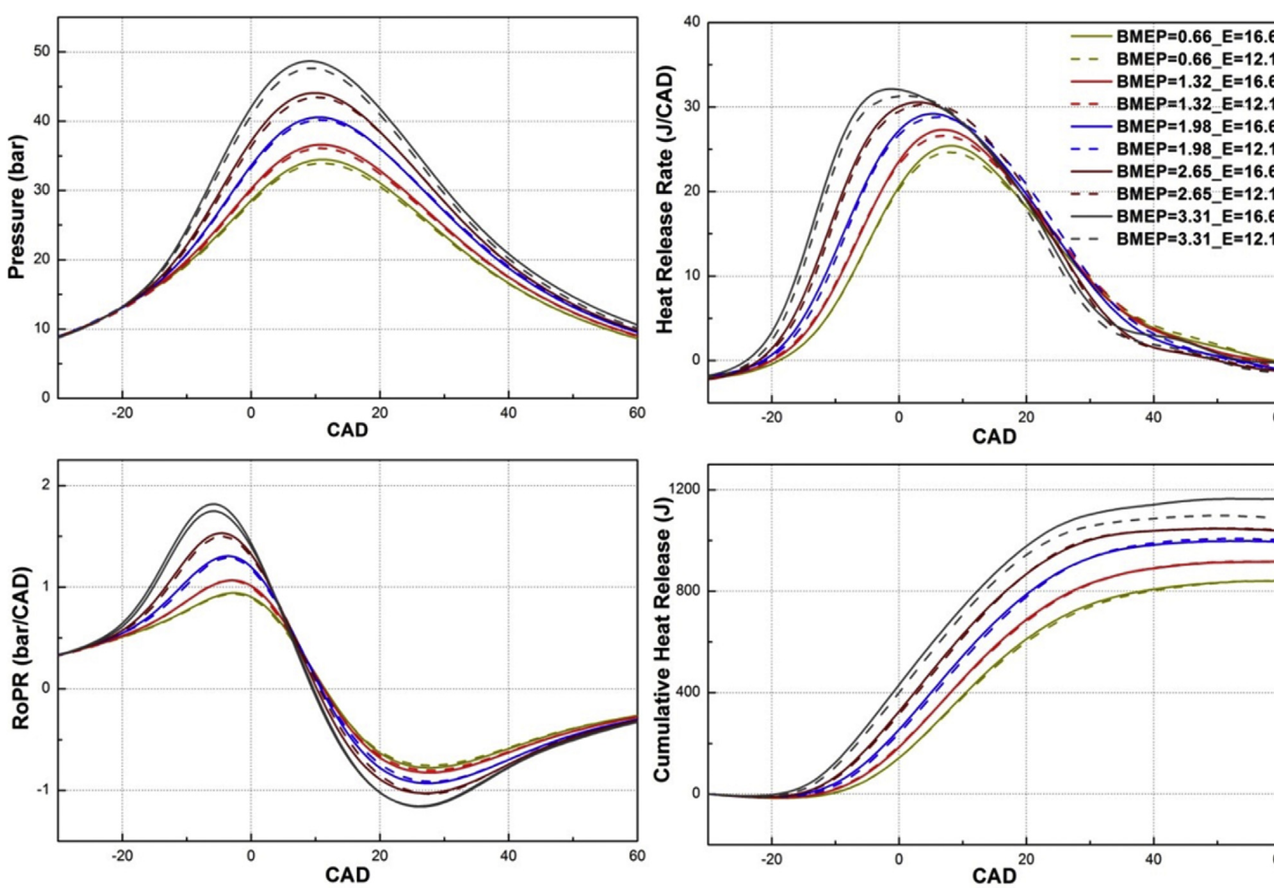

Fig. 2 – Variations of P, RoPR, HRR and CHR with crank angle position for laser ignition of hydrogen–air mixture with varying laser pulse energies.

accident. Therefore several engine hardware modifications were done to ensure safety.

Engine's cylinder head was modified to accommodate a piezoelectric pressure transducer and a customized laser spark plug. Original piston was machined from the top and the compression ratio of the engine was reduced from 17.5 to 12. An inductive type TDC proximity sensor (Transducers and Allied Product; GLP18APS) was installed close to the engine camshaft. TDC signal was acquired as a reference signal by the high speed combustion data acquisition system (Hi-Techniques; MeDAQ). A high precision shaft encoder (Encoders India, ENC58/6-720ABZ/5-24V) was installed on the engine camshaft, which converted rotational signals of the engine into corresponding voltage signals, which were subsequently acquired by the data acquisition system. A broadband lambda sensor (Bosch; LSU 4.9, 0 258 017 025) and its lambda module (ETAS; ES630.1) were installed in the exhaust pipe to measure the relative fuel–air mixture strength.

A major challenge was to design fuel injection system for gaseous fuels incorporating the desired safety features, which are essential for a fuel like hydrogen. To measure hydrogen flow rate, a coriolis force based mass flowmeter (Emerson; CMF010M) was installed in the fuel line. For ensuring safety, a flame arrestor was designed, fabricated and installed in the fuel line upstream of engine manifold. Flame arrestor absorbs heat from the flames, which may emerge from any possible backfire event and this device does not allow flames to pass through in backward direction. Another safety device 'flame trap', / water trap was also designed and fabricated. It was to doubly ensure that the flames propagating backwards do not travel and reach upto the hydrogen cylinder. A custom-built high volume flow rate solenoid fuel injector, specially designed and prototyped for injection of gaseous fuels, was used for the port fuel injection of hydrogen. It is a peak and hold solenoid injector, therefore a driver module was also used, which converts a Transistor–Transistor Logic (TTL) signal into an 8 amp peak and 2 amp hold current output. A triggering circuit was custom-built to trigger the injector at a desired crank angle position, once in each engine cycle. Inputs to the triggering circuit included (a) the TDC signal and (b) the encoder signal.

A Q-switched Nd:YAG laser (Litron, Nano L-200-30) with 1064 nm wavelength was used for the laser ignition. It delivered up to 200 mJ energy pulse with 6–9 ns duration at full width half maximum (FWHM) at the fundamental wavelength (1064 nm). For the experiments, laser energy was varied using external optical attenuator, which was installed in front of the laser head. Laser energy was attenuated by using external wave plate/polarizer setup, without disturbing any other laser parameters such as pulse duration or beam profile. Complete laser ignition system consists of two parts. One, the laser spark plug, which was fitted on the engine cylinder and converges laser beam into the combustion chamber, and two, the laser stand, which was used to hold laser source in isolation from the engine. The purpose of separating laser source from the engine was to protect it from vibrations, which could possibly damage the laser. A laser spark plug, designed and manufactured in the Engine Research Laboratory (ERL), IIT Kanpur by Srivastava and Agarwal [11], was used to transmit and focus the laser beam into the engine combustion chamber. Laser spark plug was made from two separate unit (i) lens holder and (ii) window holder. Window holder houses a sapphire window, which seals the combustion chamber and passes the laser beam from the laser spark plug to the combustion chamber. Lens holder houses a converging lens, which converges the laser beam to a focal point inside the combustion chamber. Laser stand also holds a beam reflector, and a separate unit comprising of diverging and collimating lenses [11]. After passing through the diverging and collimating lens unit, laser beam was reflected through the beam reflector. Angle of this reflector was set in a way that after getting reflected, laser beam was aligned with the axis of laser spark plug. After reflection, laser beam follows the axis of the laser spark plug, and then converges at a focal point inside the combustion chamber to form plasma. A customised electronic circuit was designed to trigger the laser pulse at the desired crank angle position in external firing mode of the laser.

An air-cooled piezoelectric pressure transducer (Kistler; 6013C) was used for measuring the cylinder pressure. The high speed combustion data acquisition system (Hi-Technique, MeDAQ) was used for acquiring the in-cylinder pressure data and further post processing. An exhaust gas emission analyzer (Horiba; Mexa 584L) was used for measuring regulated emissions such as CO, CO_2, NO, and THC. Schematic of the experimental setup is shown in Fig. 1.

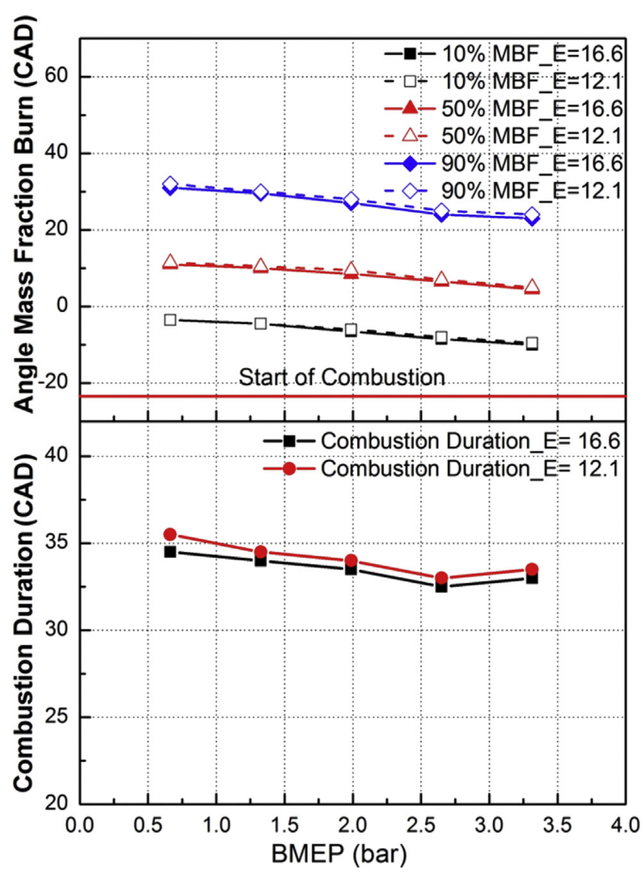

Fig. 3 – Variations of MBF and CD with load for laser ignition of hydrogen–air mixture using varying laser pulse energies.

Results and discussion

For performing the experiments, laser pulse energy was varied, while keeping the flash lamp voltage constant. Two laser pulse energies of 16.6 mJ/pulse and 12.1 mJ/pulse were used. 16.6 mJ/pulse was the maximum energy, which could be delivered by the laser source with a 2.5 mm diameter aperture (Beam quality $M^2 = 4.8$) and 12.1 mJ/pulse was the minimum laser energy, at which plasma formation was possible with 100% probability. Decreasing laser pulse energy further affected the plasma formation probability adversely, which led to engine misfire and rough engine operation. Experiments were performed with a fixed ignition timing (23° BTDC) at five different loads (BMEP's) and two laser pulse energies for comparative engine combustion, performance and emissions analysis. The data was analyzed and presented in the following sub-sections.

Combustion analysis

Combustion analysis was done using cylinder pressure data-crank angle history data. Results are compared for in-cylinder pressure (P), rate of pressure rise (RoPR), heat release rate (HRR), cumulative heat release (CHR), mass burn fractions (MBF) and combustion duration (CD). Fig. 2 shows the variation of P, RoPR, HRR and CHR with crank angle position for varying BMEP and laser pulse energy E. Average data set of 200 consecutive engine cycles acquired by the high speed data acquisition system at every test condition, was chosen for further analysis of combustion parameters. P_{max} increased with increasing BMEP for both laser pulse energies. At lower BMEP, difference in P_{max} for both pulse energies is almost negligible but with increasing BMEP, this difference in P_{max} increased. RoPR also increased with increasing BMEP as well as increasing laser pulse energy (Fig. 3). At higher laser pulse energy, HRR was relatively higher. For fixed laser pulse energy, HRR increased with increasing BMEP.

P, HRR and RoPR increased with increasing BMEP because higher quantity of hydrogen was introduced into the combustion chamber in each engine cycle for producing desired power output. In addition, at higher BMEP, combustion started relatively earlier, leading to higher RoPR and P_{max}, closer to TDC. Laser beam can propagate into the interiors of plasma. After plasma formation, it absorbs laser energy more strongly [12,13]. However plasma can absorb energy up to a certain threshold and beyond that, plasma intensity does not vary significantly with further increase in laser pulse energy [14]. At higher laser pulse energy, energy density of plasma increases, leading to relatively earlier start of combustion (SOC) (Fig. 3). Therefore at constant BMEP, higher laser pulse energy (16.6 mJ/pulse) increased P_{max}, HRR and RoPR compared to lower pulse energy (12.1 mJ/pulse). CHR increased with increasing BMEP due to higher fuel quantity inducted at

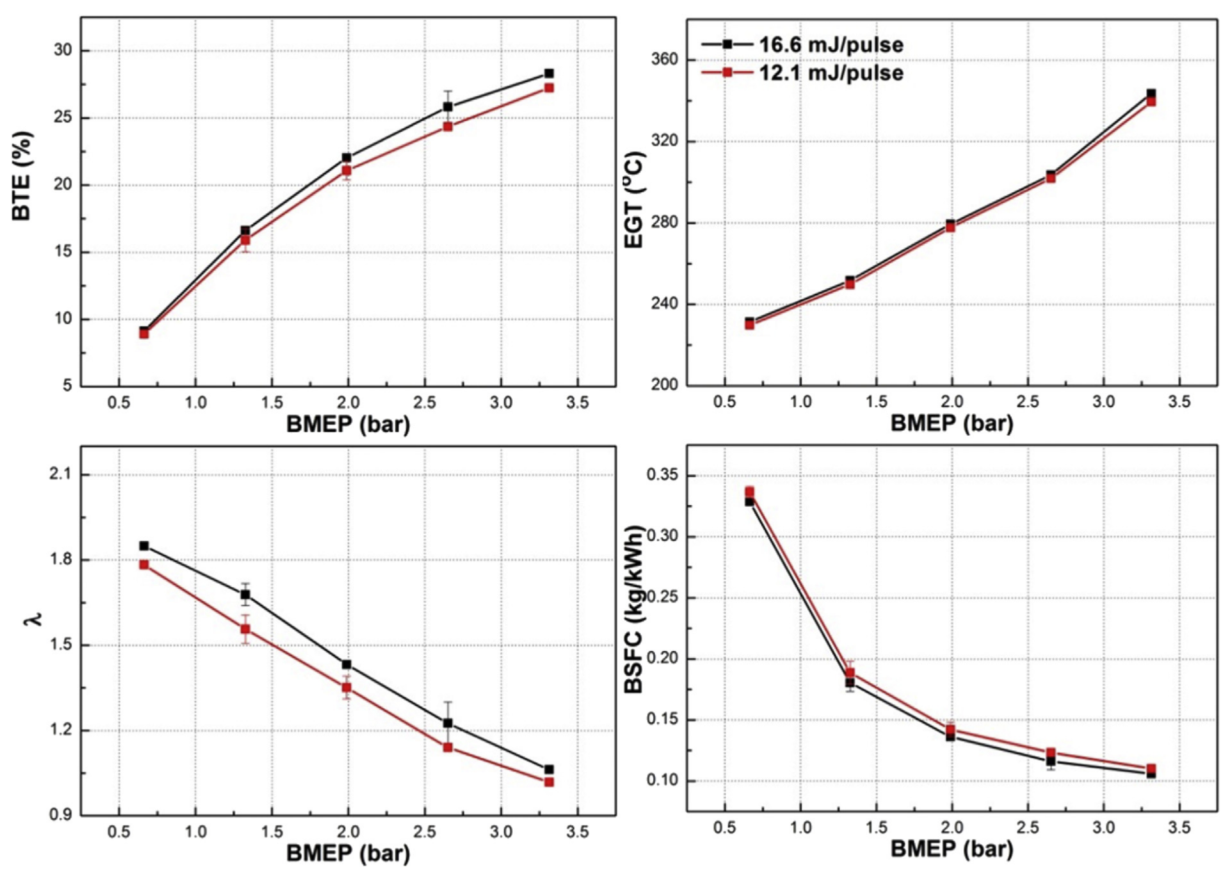

Fig. 4 – Variations of BTE, λ, EGT and BSFC with BMEP for laser ignition of hydrogen–air mixture with varying laser pulse energies.

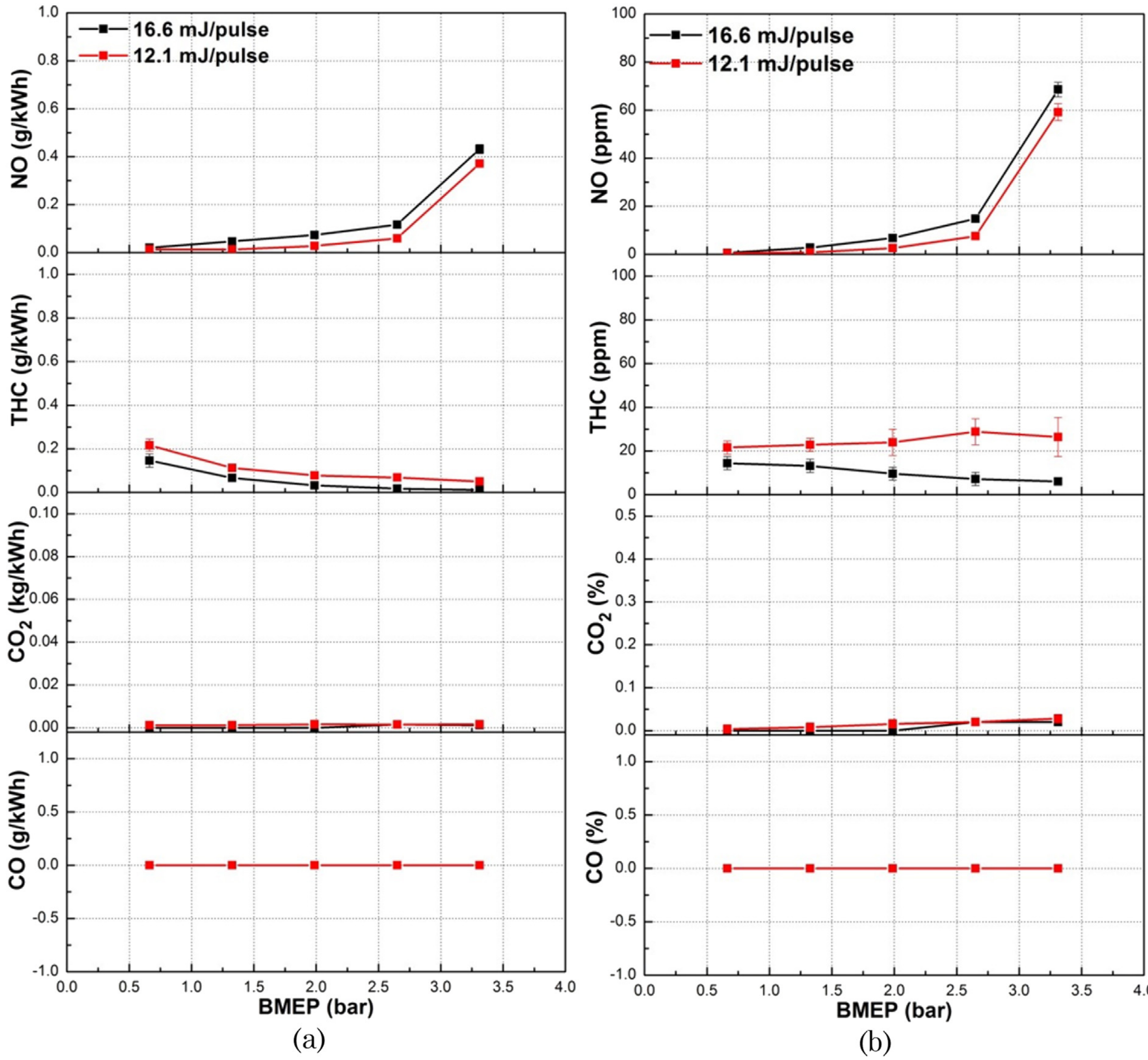

Fig. 5 – Variations of (a) mass emissions (g/kwh), and (b) raw emissions (ppm/%) with load for laser ignition of hydrogen–air mixture with varying laser pulse energies.

higher BMEP. Additionally, for a fixed BMEP, CHR was relatively higher for higher laser pulse energy due to superior combustion efficiency achieved by higher energy laser pulse.

Relatively earlier SOC for higher laser pulse energy is evident from Fig. 3, which shows crank angle position for 10%, 50% and 90% mass burn fraction (MBF). It is seen that SOC (i.e. 10% MBF) decreased with increasing BMEP for both laser pulse energies. SOC for E = 16.6 mJ/pulse advanced compared to SOC for E = 12.1 mJ/pulse due to higher energy density plasma formed by higher pulse energy. For lower BMEP, SOC for both laser pulse energies was almost similar.

Fig. 3 also shows that CD was shorter for higher laser pulse energy. CD first decreased with increasing BMEP and then remained almost constant. This was possibly due to higher fuel quantity, which continued to burn in the after-burning phase at higher load. For higher laser pulse energy, overall CD was lower at all BMEPs.

Performance analysis

Engine performance was evaluated by determining brake thermal efficiency (BTE), relative air–fuel ratio (λ), brake specific fuel consumption (BSFC) and exhaust gas temperature (EGT) for different laser pulse energies. Since SOC was relatively advanced for higher energy laser pulse, combustion of hydrogen was more efficient. Advanced SOC meant higher fuel quantity was undergoing combustion, when the piston was closer to TDC. Near TDC, combustion chamber pressure was higher, leading to increased fuel–air mixture density, which led to superior combustion and increased combustion efficiency. This led to relatively superior BTE for higher laser pulse energy (Fig. 4). λ shows the availability of excess air in the engine combustion chamber. At high loads, higher fuel quantity is inducted into the engine combustion chamber, which leads to reduction in λ for both E = 16.6 mJ/pulse and

12.1 mJ/pulse. λ for higher pulse energy was slightly higher because at higher laser pulse energy, lesser hydrogen quantity was required to generate same power output (due to improved BTE, Fig. 4).

EGT for higher laser pulse energy was also relatively higher (Fig. 4) due to higher HRR (Fig. 2). Difference in EGT between the two laser pulse energies was insignificant. At 1.98 bar BMEP, temperature difference between two laser pulse energies was merely 1.6 °C, which was statistically insignificant.

BSFC decreased with increasing BMEP for both laser pulse energies (Fig. 4). For constant laser pulse energy, reduction in BSFC was primarily due to higher BTE. As BTE increased, lower hydrogen quantity was required per unit power output. Therefore BSFC for higher laser pulse energy was relatively lower due to its superior BTE (Fig. 4).

Emissions analysis

Emission analysis from the laser ignited hydrogen engine with two different laser pulse energies was done for THC, CO, NO, and CO_2. Mass emissions and raw exhaust emissions from the laser ignited hydrogen fuelled engine with different laser pulse energies are shown in Fig. 5. NO emission for higher laser energy was also relatively higher. Higher NO emission was due to higher HRR observed with higher energy laser pulse (Fig. 2). This was also reflected in the results of EGT variations (Fig. 4). Relatively higher peak in-cylinder temperature in the engine combustion chamber with higher pulse energy may increase NO emission.

Fig. 5 also shows THC, CO_2 and CO emissions at different engine loads. It can be observed that CO was almost zero for both laser pulse energies. THC and CO_2 emissions were very low in both cases and their comparison is an insignificant exercise because the absolute values of these emissions were low enough to be inconsequential. This was primarily due to total absence of carbon in the test fuel i.e. hydrogen.

Miniscule quantity of THC and CO_2 emissions were produced because of combustion of lubricating oil in the engine combustion chamber. Lubricating oil present on the cylinder liner surface and crevice volume gets splashed out into the combustion chamber along with crevice gas, as well as due to piston ring dynamics, which leads to minor THC and CO_2 formation. However these emissions were insignificant compared to a hydrocarbon fuelled SI engines.

Conclusions

Experiments were carried out to study the effect of laser pulse energy in a laser ignited prototype hydrogen engine on its combustion, performance and emissions characteristics. From the experimental results, following conclusions were drawn:

1. Peak in-cylinder pressure, rate of pressure rise and heat release rate were higher for higher laser pulse energy of the laser ignited hydrogen fuelled engine.
2. Start of combustion was relatively advanced for higher energy laser pulse but the combustion duration was relatively shorter.
3. Engine performance parameters namely brake thermal efficiency, relative air–fuel ratio, and brake specific fuel consumption were relatively superior for laser ignition using higher energy pulse.
4. Exhaust gas temperature for higher energy laser pulse was slightly higher at all loads, leading to relatively higher NO formation. Other regulated emissions such as total unburned hydrocarbons, carbon monoxide and carbon dioxide were insignificant in the exhaust.

In summary, laser ignition with higher energy laser pulse improved overall engine performance in a laser ignited hydrogen fuelled engine.

Acknowledgments

The authors would like to acknowledge research grant from Ministry of New and Renewable Energy (MNRE), Government of India for carrying out this investigation (Grant No. 103/138/2008-NT dated 26-12-2011). Gaurav Verma, helped in carrying out experiments along with Mr. Roshan Lal and Mr. Hemant, Technical staff members of Engine Research Laboratory, IIT Kanpur.

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