Fuel 123 (2014) 113–122

Contents lists available at ScienceDirect

Fuel

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

Comparative experimental evaluation of performance, combustion and emissions of laser ignition with conventional spark plug in a compressed natural gas fuelled single cylinder engine

Dhananjay Kumar Srivastava, Avinash Kumar Agarwal *

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

HIGHLIGHTS

- Comparative evaluation of laser ignition (LI) and spark ignition (SI).
- Air–fuel ratio and ignition timings were varied.
- Brake power was marginally higher for LI compared to SI.
- Combustion advanced in LI by 1–4° CA compared to SI.
- COV_{IMEP} in LI was lower compared to SI.

ARTICLE INFO

Article history:
Received 9 December 2013
Received in revised form 11 January 2014
Accepted 13 January 2014
Available online 28 January 2014

Keywords:
Laser ignition
Spark ignition
Laser pulse energy
Plasma
Compressed natural gas

ABSTRACT

Laser is emerging as a strong concept for alternative ignition in spark ignition engine. Laser ignition has potential advantages over conventional spark plug ignition. Laser ignition system is free from spark electrodes hence there is no loss of spark energy to the electrodes, which are also free from erosion effect. In addition, there is flexibility in choosing spark location and it offers excellent performance under high in-cylinder pressures. In this paper, performances of laser ignition and conventional spark ignition systems are comparatively evaluated in terms of in-cylinder pressure variation, combustion stability, fuel consumption, power output and exhaust emissions at similar operating conditions of the engine.

1. Introduction

Stringent norms for engine exhaust emissions and demand for higher thermal efficiency have compelled the automotive manufacturers and researchers to develop new engine technologies and alternative fuels. Compressed natural gas (CNG) is one of the most promising alternative fuel because of its widespread availability, economic viability and environmental benefits. CNG fuelled engine can be operated with higher compression ratio because of its high octane number compared to gasoline, which results in superior thermal efficiency and reduced fuel consumption. Engine exhaust emissions are lower compared to other hydrocarbon fuels due to its high hydrogen-to-carbon ratio. Engine exhaust emissions can be reduced by in-cylinder combustion optimization and exhaust gas after-treatment. Therefore, it is of great interest to introduce engine technologies, which can address the need for both improved thermal efficiency and reduced engine exhaust emissions. Lean mixture combustion is a promising concept to increase engine efficiency and reduced exhaust emissions from spark ignition engines [1–3]. However, lean mixture combustion is associated with two major challenges namely loss of power output and slower flame speeds. These challenges restrict the lean limit of air–fuel mixtures. Full potential of lean mixture combustion can be extracted by overcoming these two challenges.

Loss of engine power output can be compensated by boosting the charge density in the combustion chamber. Increased charge density however requires higher secondary coil voltage to initiate combustion in a spark ignition engine, which is using conventional spark ignition system. The voltage required to produce the spark depends on factors such as pressure inside the combustion chamber at the time of ignition, distance between the electrodes, and cylinder gas temperature. Providing the required voltage under these conditions would lead to spark electrode erosion. Since lean

* Corresponding author. Tel.: +91 512 2597982; fax: +91 512 2597408.
E-mail address: akag@iitk.ac.in (A.K. Agarwal).

http://dx.doi.org/10.1016/j.fuel.2014.01.046
0016-2361/

mixtures have relatively slower flame speed than stoichiometric mixtures, any technique which may provide a stronger and reliable initial flame kernel or increase the air–fuel mixture burning rate, would be beneficial. Flame speed in the lean burn SI engine can be increased either by generating turbulence in the cylinder [4] or by shortening the flame travel distance for the same mixture strength. Reduction in flame travel path can be realized by employing multiple spark plugs in each cylinder or by placing the ignition point at an optimum location inside the combustion chamber [5,6]. It is rather challenging to install multiple spark plugs in multi-cylinder engines because of already overcrowded cylinder head. Optimum spark location inside the combustion chamber is also difficult in case of conventional spark ignition systems because spark location is always very close to the top of combustion chamber. Therefore, a durable, high-energy, electrode-less ignition system with controlled energy deposition in the plasma, with flexibility to change the ignition location is a desirable option for overcoming these limitations faced in lean-burn SI engines. Laser ignition system meets most of these requirements and, offers several advantages for igniting lean mixtures.

The concept of laser ignition is based on focusing the pulsed laser beam tightly to create a very small spot size in such a manner that the energy density at the focal point is enough to generate a localize plasma (Fig. 1). Laser pulse energy is further absorbed by the plasma to raise the local temperature and pressure. If the energy threshold is high enough, ignition takes place in the surrounding air–fuel mixture.

There are different mechanisms by which laser interacts with gaseous medium to initiate combustion such as (i) thermal ignition [7–10], (ii) photochemical ignition [11–13], (iii) resonant ignition [14] and, (iv) non-resonant ignition [15–18]. For engine applications, non-resonant mechanism is generally used because in this mechanism, where laser wavelength is independent of the absorption wavelength of gaseous molecules. Laser ignition was done in this study using non-resonant mechanism. Laser ignition offers several advantages over conventional spark plug ignition system for engine applications. Minimum ignition energy required for combustion decreases with increasing cylinder pressure using laser ignition [15]. This trend is exactly opposite of what is observed in conventional spark ignition system, where spark energy required for combustion increases with increasing cylinder pressures [19]. Location of ignition point in the combustion chamber can be optimized in laser ignition by changing the focal length of the converging lens. Flame kernel can be moved away from the combustion chamber walls thus the heat transfer losses through the cylinder walls can be reduced thereby enhancing the overall efficiency. It is expected that ignition delay and combustion duration will be shorter in laser ignition compared to conventional spark plug ignition. Thus NOx emission will be lower in laser ignition. There are no heat losses at spark electrodes in case of laser ignition because this is an electrode-less ignition concept. Thus approximately entire laser pulse energy can be transferred to the combustible mixture using an optimized laser and optics. This helps in initial flame kernel development which influences the combustion and cycle-to-cycle variations.

Several researchers have investigated combustion using laser ignition in a constant volume combustion chamber, which simulated typical engine operating conditions towards the end of compression stroke [15–18,20–24]. Several parameters like minimum ignition energy, flame kernel evolution, ignition delay, rate of pressure rise, effects of laser and optics, etc. were measured for different fuels in these studies. These experiments were helpful in developing laser ignition system for engine. Srivastava et al. [24] carried out laser ignition of CNG–air mixture in a constant volume combustion chamber and investigated evolution of flame kernel for varying lambda. In the early stages of flame development, a toroidal shape of the kernel was observed. Toroidal shape of flame kernel was similar to conventional spark plug ignition system. After some time, a front lobe formed, which propagated towards the incoming laser beam. This was a peculiar feature of laser-induced ignition. The shape of the flame kernel was structurally identical for all air–fuel ratios. It was observed that the front lobe of the flame kernel disappeared after some time for relative air–fuel ratios (λ) of 1.6 and 1.7. Dale et al. [25] first demonstrated laser ignition of an internal combustion engine in 1978. They compared the engine performance using laser ignition vis-a-vis conventional spark plug system. Higher rate of pressure rise was reported for laser ignition. Lean limit of air–fuel ratio was extended from 22.5:1 to 27.8:1 for the laser ignition. Over the years, laser ignition of engine did not gather momentum due to good performance offered by conventional spark plug systems and poor efficiency and high cost of lasers available. However, stringent emission legislations and increased emphasis on lean-burn combustion are compelling the engine developers and scientists around the world to consider laser as an ignition source for the internal combustion engines. Biruduganti et al. [26] compared the laser and conventional spark ignition systems on a natural gas engine at fixed λ by varying the spark timing. They reported that fuel conversion efficiency and COV of IMEP were comparable for both ignition systems. Laser ignition performed much better compared to spark ignition due to higher peak pressures and faster combustion. NOx emission was higher for laser ignition compared to spark ignition at identical operating condition of the engine. Bihari et al. [27] conducted laser ignition of single cylinder research engine fuelled with CNG. Lean misfire limit extended from an equivalence ratio of 0.55–0.50 with laser ignition at 900 rpm engine speed. Combustion stability was

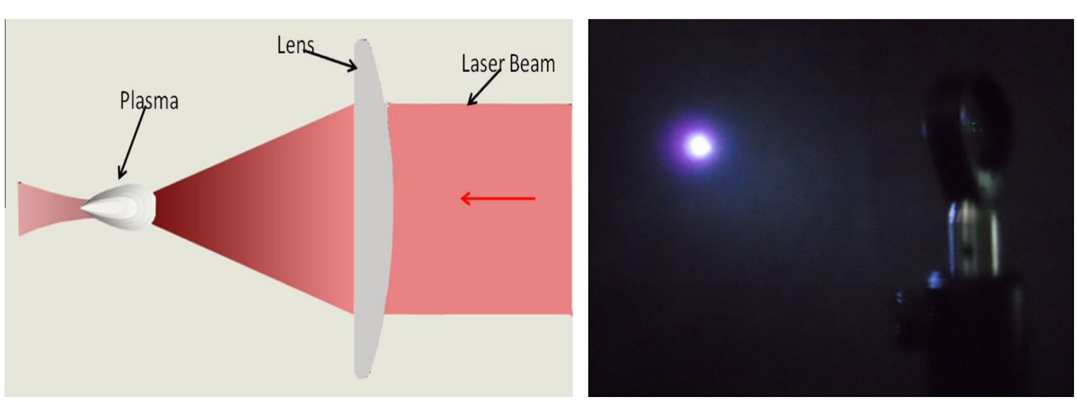

Fig. 1. Plasma formation in air (direction of incoming laser is from right to left).