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Combustion characteristics of a variable compression ratio laser-plasma ignited compressed natural gas engine

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ABSTRACT

Compressed natural gas (CNG) is considered as one of the most promising alternative fuel used in transport sector worldwide with great potential. However it suffers from the problem of high NOx emissions in a stoichiometric engine. Stringent emissions norms and demand for high thermal efficiency can be met by ignition of lean fuel-air mixtures, which do not produce oxides of nitrogen (NOx). However lean combustion is associated with slower flame speed and lower power output. Lean mixtures are very difficult to ignite by conventional electrical spark generated plasma therefore this comes across as a severe limitation, if one tries to develop a lean-burn conventional CNG engine capable of meeting future emission requirements. Ignition system of a spark ignition (SI) engine is responsible for initiating combustion of fuel-air mixture inside the combustion chamber. However, current ignition systems face limitations in catering to requirements of high efficiency, and high power density, which are essential for an environment friendly SI engine. Laser ignition system is an alternative and technically viable ignition system for igniting lean fuel-air mixtures in IC engines and is capable of overcoming most limitations faced by conventional electrical spark ignition systems. In this paper, laser ignition of lean CNG-air mixtures is experimentally investigated at different compression ratios and air-fuel ratios, in order to extract full potential of CNG for transport applications. It is found that lean flammability limit with drivability constraints increased from $\lambda = 1.62$ to $\lambda = 1.76$ with increased compression ratio from 9.9 to 11.8, which reflects the benefits offered by higher compression ratio application in laser ignition of CNG-air mixtures, which will be vital for developing lean-burn CNG engine.

1. Introduction

Increasing concerns about environment issues arising because of engine emissions and depletion of fossil fuels have motivated search for a sustainable alternative fuel for the transport sector. Stringent emission legislations, demand for high thermal efficiency and lower fuel consumption require quantum improvement in engine technology and fuels. Compressed natural gas (CNG) is considered as one of the most promising alternative fuels used in transport sector with great potential worldwide, and it is one of the cleanest and cheapest commercial alternative fuel available today. A closer look at the properties of CNG brings in important aspects regarding its feasibility for internal combustion (IC) engines. CNG diffuses faster in air compared to gasoline and diesel, leading to easier engine starting, reliable idling, more efficient combustion, and lower hydrocarbon emissions. Octane number of CNG is 120 compared to 87–93 for gasoline. A high octane number entails to higher knock resistance. Therefore dedicated CNG engines can be designed for higher compression ratio compared to gasoline engines, which would improve their thermal efficiency and fuel economy [1–3]. CNG can be used in a bi-fuel mode configuration in a gasoline engine, where the fuel system can be modified to operate either on gasoline or CNG, therefore the compression ratio of engine needs to be determined according to gasoline requirements. Flammability limit of CNG (5–15% v/v) is comparatively wider than gasoline (1.3–7.2% v/v), thus making it possible to operate the CNG engine with greater flexibility in relative air-fuel ratio (λ) [4].

Oxides of nitrogen (NO_x) are the most important pollutants of concern from CNG engines. NO_x formation depends on peak in-cylinder temperature and the residence time of the charge at this temperature [5]. Emissions from CNG engine can be improved by operating the engine with lean fuel-air mixtures. However, this also leads to reduced power output. Power output from lean fuel-air mixtures can be increased by boosting the engine. High in-cylinder pressure of lean fuel-air mixtures at the time of combustion requires relatively higher voltage, when conventional spark ignition system is used [6]. Minimum voltage to initiate combustion successfully (i.e. to generate spark

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plasma) depends strongly on the in-cylinder pressure at the time of spark generation and the distance between the spark plug electrodes. Higher is the in-cylinder pressure, higher spark plug voltage is required for successful ignition. Providing necessary spark voltage for igniting lean CNG-air mixtures at higher in-cylinder pressure reduces the spark plug life because of severe electrode erosion. This limitation of conventional spark plugs has motivated research for alternate ignition systems, which are capable of overcoming this issue. There are several types of advanced ignition systems under consideration, which can increase the ignition energy and hence the flame speed. These include breakdown ignition system, corona spark plugs [7,8], plasma jets [9], rail plug igniters [10], combustion jets [11], and radio frequency spark plugs [12]. Unfortunately higher spark energies are also associated with higher erosion of spark electrodes thus shortening the life of the spark plug [13]. Furthermore, the electrodes act as a thermal energy sink. A considerable amount of spark plasma energy is therefore absorbed by the electrodes thus reducing the amount of energy transferred to the combustible fuel-air mixture for ignition. In order to realize combustion of leaner CNG–air mixtures at higher in-cylinder pressures, a durable high-energy electrode-less ignition system is a desirable option, which would be able to overcome these limitations.

Laser could be an alternative energy source for ignition in an engine. The basic idea of laser ignition is to create plasma spark by focusing a laser beam, which will ignite combustible fuel-air mixture. Hickling et al. [14] demonstrated use of laser plasma in igniting a wide range of combustible fuel-air mixtures in a constant volume combustion chamber (CVCC). Laser ignition of engine was first demonstrated by Dale et al. [15] in 1978. However, laser induced combustion, especially for engine applications could not gather momentum due to reasonably good performance of conventional spark plug based systems, which were developed subsequently. Stringent emission legislations have also evolved with time due to global warming hence emphasis is now shifting on developing lean-burn engines. Lasers could therefore be considered as an ignition source for such lean-burn engines in future.

Fundamental of laser induced ignition and effects of different parameters such as lasers, optics, pressure, and air-fuel ratio, on combustion have been extensively investigated in a CVCC [16–23]. Biruduganti et al. [24] compared laser ignition and conventional spark ignition in a single cylinder engine fuelled with natural gas. Conventional spark ignition used 125 mJ/spark ignition energy, while only 31 mJ/pulse laser energy was used in laser ignition. They concluded that laser ignition led to superior combustion compared to spark ignition due to higher peak pressures, faster burning and better HRR at identical operating conditions. Srivastava et al. [25] also compared the laser ignition system with conventional spark ignition system in a CNG fuelled single cylinder engine. They concluded that maximum cylinder pressure and HRR were marginally higher for laser ignition compared to spark ignition for identical mixture strength and ignition timings. CoV of IMEP also improved in laser ignition compared to conventional spark ignition. Bihari et al. [26] conducted laser ignition in a single cylinder research engine fueled with natural gas and compared its results with conventional capacitance discharge ignition (CDI) system. Experiments were performed at 15 bar BMEP at 900 rpm engine speed. It was found that lean misfire limit got extended from an equivalence ratio of 0.55 to 0.50 due to laser ignition. Combustion stability also improved for retarded ignition timings. Because of these two reasons, approximately 50% NOx reduction was observed in case of laser ignition. McMillian et al. [27] performed laser ignition in a lean-burn natural gas fuelled engine. They found that with laser ignition system, total operating envelope of the engine which is defined as the area between knock and misfire limit, increased by 46% compared to conventional spark ignition system. Liedl et al. [28] demonstrated laser ignition successfully in a gasoline direct injection (GDI) engine. Compared to conventional spark ignition, laser ignition reduced the fuel consumption significantly, and reduced the emissions by ~20%. Herdin et al. [6] carried out laser ignition experiments in a large-bore natural gas engine. They reported that the energy required for producing plasma decreased with increasing cylinder pressure. Therefore higher charge density in the combustion chamber was a favourable condition for laser ignition, which was exactly reverse of electrical spark ignition.

Laser ignition has potential to overcome other limitations of the conventional spark ignition system such as spark plug erosion, heat loss to the electrodes, and offers excellent performance even at high cylinder pressures, in addition to offering possibility in choosing spark location inside the combustion chamber, and multi-point ignition. Lean-combustion faces two major constraints namely low power density and slower flame speed. The choice of plasma location inside the combustion chamber is one of the several advantages offered by laser ignition. Location of ignition initiator spark can be chosen at any optimum point inside the combustion chamber, using a suitable focal length of the converging lens or by changing the position of the converging lens in the optical spark plug. This is not practically feasible in case of a conventional spark ignition system. This way, flame propagation distance could be reduced and combustion duration could also be shortened effectively [29,30]. Reduction in power density can be compensated by using turbocharging. However, under these circumstances, lean fuel-air ratio and high in-cylinder pressure require higher secondary voltage to ignite the fuel-air mixture in the conventional ignition system, eventually reducing the life of the spark plug [31]. In a conventional spark ignition system, breakdown voltage required for combustion increases directly with electrode gap and pressure in the combustion chamber at the time of ignition [32]. Smaller electrode gap leads to flame quenching. Laser ignition system is electrode-free and lasers available in the market offer quite long lifetime and steady performance [33]. On the other hand, minimum energy required for ignition decreases with increasing in-cylinder pressure in case of laser ignition due to superior absorption of laser energy [34]. Primary goal of this study is therefore to examine laser ignition system at high pressure conditions inside an engine combustion chamber. In this paper, laser ignition is experimentally investigated in an engine to ignite CNG-air mixtures while varying engine's compression ratio as well as air-fuel ratio to investigate their effects on engine's combustion, performance, and emission characteristics.

2. Experimental setup

Since it is difficult to have flexibility in altering various parameters in a production grade SI engine for experimental investigations such as compression ratio, spark timing and air-fuel ratio, a single cylinder diesel engine was modified to act as a spark ignition engine, and customised to operate on CNG for this study. It is also difficult to modify a cylinder head of a production grade SI engine to accommodate a laser spark plug and a pressure transducer because the cylinder head is quite crowded in the first place. Using a diesel engine to develop such a prototype offers desired strength of various components, which is essential for experiments in an unchartered territory. This prototype test engine was then coupled to an eddy current dynamometer, which control led its speed and load. Dynamometer was connected to a 3φ A/C motor through a gear box, which was engaged to start the engine and was disconnected, once the engine started. The schematic of the experimental setup is shown in Fig. 1.

Since CNG is stored at very high pressure, a pressure reducer is employed to bring CNG pressure down to 1 bar for these experiments. Low pressure fuel line was then connected upstream of throttle in the air intake system. CNG mass flow rate was measured by a Coriolis force mass flow meter (Emerson; CMF010M). A laminar flow element (LFE) (Meriam; 50MC2-2F) was installed for the intake air flow rate measurement. In this investigation, compression ratio of the engine was varied by changing the pistons having different piston bowl volume to change the clearance volume. Compression ratio of the original diesel engine was 17.5. Compression ratio of the modified prototype engine

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