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Combustion characteristics and flame-kernel development of a laser ignited hydrogen–air mixture in a constant volume combustion chamber

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ABSTRACT

Laser ignition of hydrogen–air mixture was carried out in a constant volume combustion chamber (CVCC) at 10 bar initial chamber filling pressure and 373 K chamber temperature. A Q-switched Nd:YAG laser at 1064 nm with a pulse duration of 6–9 ns was used for plasma generation and ignition of combustible hydrogen–air mixture. Pressure–time history of different hydrogen–air mixtures was measured in the CVCC and flammability limits of hydrogen–air mixture were measured. Flame kernel development was investigated for different air–fuel mixtures using Shawdowgraphy and flame propagation distances were calculated. Minimum ignition energy was measured for hydrogen–air mixtures of different air–fuel ratios and effect laser pulse energy on pressure–time history in the CVCC was experimentally measured. Upon increasing the laser pulse energy, time taken to attain peak cylinder pressure reduced which resulted in faster combustion in hydrogen–air mixtures however the peak cylinder pressure remained similar.

1. Introduction

Engine manufactures are currently seeking to develop internal combustion (IC) engines, which are more fuel efficient, refined and produce lower emissions, and are capable of using alternate fuels such as biodiesel, alcohols, CNG, hydrogen etc. In recent years, hydrogen fuelled IC engines have become increasingly attractive, first because of their extremely low pollution potential, and second because of the potential use of hydrogen as synthetic fuel. The only harmful pollutant emitted by combustion of hydrogen–air mixture is NO_x. Hydrogen is perhaps an ideal fuel in view of its ability to be generated from a host of primary renewable energy sources. Hydrogen is a unique and versatile fuel, which has the potential to provide solution for fossil fuel depletion and global environmental issues simultaneously. A close look at the fuel properties of hydrogen brings in very important aspects w.r.t. its feasibility for engine operation. Interestingly, most of the properties of hydrogen if exploited appropriately, would prove to be points of advantage and will be desirable. Hydrogen has a wide flammability range in comparison to all other known fuels, therefore it is very easy to operate hydrogen engine with extremely lean mixtures. Hence, fuel economy will be greater and the combustion reactions would also be complete to a greater degree. Additionally, maximum

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combustion temperatures inside the combustion chamber would also be lower for lean air–fuel mixtures compared to stoichiometric mixture, which would reduce the noxious pollutants [1,2]. In addition, stoichiometric hydrogen–air mixture has an extremely low ignition energy requirement, higher flame speed and higher diffusivity compared to stoichiometric gasoline–air mixture [3]. However, extremely low ignition energy makes the system susceptible to surface ignition. Surface ignition is a highly undesirable combustion phenomenon caused by uncontrolled ignition of fuel–air mixture and can be initiated by an overheated valve or a spark plug, glowing combustion chamber deposits, or any other hot spot in the combustion chamber [4]. The surface ignition may occur even before the spark plug initiates normal ignition or sometimes after the normal spark. Because of surface ignition, the spark discharge no longer has complete control on the combustion process, which has severe implications upon engine operation and structural safety.

Since, hot tip of a spark plug is the most suspected source of surface ignition in a hydrogen fuelled engine, an electrode-free ignition system should be considered for developing a commercial hydrogen fuelled IC engine. An alternative solution to standard spark plug is the use of a pulsed laser, which may be focused to generate intense plasma, representing laser ignition. Stringent emission norms and demand for high thermal efficiency can also be met by igniting relatively leaner fuel–air mixtures. However, such mixtures lead to lower power density therefore lower power output also. Loss of power output can be compensated by increasing intake charge pressure by employing turbocharging, which also leads to higher in-cylinder pressures. Higher in-cylinder pressure at the time of ignition however requires higher voltage to ignite the combustible mixture in a conventional spark ignition system. Such high voltages unfortunately lead to rapid spark electrode erosion therefore lowers the life span of the spark plugs. However, higher in-cylinder pressures are in fact a favorable condition for laser ignition because minimum ignition energy required for initiating combustion actually decreases with increasing cylinder pressure [5]. In view of these special features, laser ignition has significant potential to ignite relatively leaner mixture without loss of power output in addition to reducing emissions.

Laser ignition has been a subject of research since 1970's. Use of laser pulses for ignition of combustible air–fuel mixture has several advantages over conventional spark ignition such as possibility of free positioning of plasma, absence of electrode erosion effects, feasibility to ignite leaner mixtures, precise ignition timings etc. Furthermore, with the possibility of multipoint ignition, combustion can be initiated by two or more plasma sparks at multiple locations at the same time in the combustion chamber, which can possibly shorten the combustion duration significantly because of reduction in maximum distance of flame travel [6,7]. Major reasons to prefer laser ignition over conventional spark ignition is the feasibility of a having lower lean limit for ignition together with higher ignition pressures, leading to higher efficiency and significantly lower NO_x emissions [8].

Studies in the past reported successful and reliable laser ignition of CNG-air mixtures [9]. However only few such studies have been done for hydrogen. Ma et al. [10] found that the flame velocity in laser ignited gas mixtures is faster than in conventionally ignited mixtures. Using laser ignition, pressure rise in the combustion chamber was seen to be significantly higher compared to conventional spark ignition under identical conditions [11]. Weinrotter et al. [12] and Srivastava et al. [5] also showed that peak cylinder pressure decreased as the relative air–fuel ratio (λ) of the mixture increased i.e. mixture became leaner. Morsy et al. [13] showed that using multi-point laser ignition leads to faster combustion of fuel–air mixture with no significant change in the peak pressure. Changjian et al. [14] showed that flame velocity increased upon increasing initial pressure as well as increasing laser pulse energy.

In light of these studies, the present experimental study was focused on investigating different aspects of laser ignited hydrogen–air mixture in a constant volume combustion chamber (CVCC). Different stages of flame kernel development were captured and analyzed to find flame speed and flame kernel evolution with time. Pressure–time history and net heat release were also measured for hydrogen–air mixtures of varying relative air–fuel ratios.

2. Experimental setup

The experimental setup included laser for plasma ignition and a CVCC. A high speed camera and a piezoelectric pressure transducer were used for visualizing flame kernel evolution and measuring the in-cylinder pressure–time history respectively. Experiments were performed on different hydrogen–air mixtures prepared using Zero grade hydrogen and moisture free compressed air, which were mixed to form homogeneous combustible mixture. For achieving the intended fuel–air ratio, Dalton's law of partial pressures was used. The partial pressures of hydrogen and air were measured using two high resolution digital manometers (Thommen; HM35). After each experiment, the CVCC was evacuated to 2.5 mbar using a vacuum pump. Then hydrogen was filled to the calculated partial pressure. Air was then introduced into the CVCC to take it upto the final pressure. Hydrogen has very high diffusion coefficient (0.61 cm^2/s). Hydrogen was introduced in the geometrical center of CVCC. Therefore the maximum diffusion area was 11 cm × 7.2 cm. The diffusion time was calculated by the equation $t = X^2/2d$, where X is the longest dimension (11 cm) and d is the diffusion coefficient (0.61 cm^2/s). Therefore the time required for diffusion of hydrogen air-mixture is 99.18 s. Mixture was therefore allowed to diffuse for homogenization for 2 min before the ignition experiment. Initial temperature of CVCC was maintained at 373 K using finger heater of adequate capacity and a PID controller, in order to simulate the engine combustion chamber conditions prevailing at the time of ignition. The CVCC was installed with finger heaters (6 Nos; 750 W each) to heat the chamber contents. The temperature of CVCC was measured using a thermocouple located in the central section. Heating was controlled and the temperatures were maintained using the PID controller. Fig. 1 illustrates the schematic of the experimental setup. Details of the experimental setup can be found in our research paper listed as reference [15].