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A study of laser induced ignition of methane–air mixtures inside a Rapid Compression Machine

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Abstract

Presented herein is a fundamental study of laser ignition of methane/air mixtures at temperatures and pressures representative of an internal combustion engine. An Nd:YAG laser operating at $\lambda = 1064$ nm was used to ignite methane/air mixtures at equivalence ratios of $0.4 \leq \Phi \leq 1$ in a Rapid Compression Machine (RCM). Experiments were conducted to study the lean limit, minimum spark energy (MSE), and minimum ignition energy (MIE). The results show that laser ignition exhibits a stochastic behavior which must be interpreted statistically. A 90% probability of occurrence was used to evaluate the MSE and MIE, which resulted in $\text{MSE}_{90} = 2.3$ mJ and $\text{MIE}_{90} = 7.2$ mJ at an equivalence ratio $\Phi = 0.4$ at compressed pressure and temperature of $P_{comp} = 29$ bar and $T_{comp} = 750$ K, respectively. The lean limit was characterized based on the fraction of chemical energy converted into thermal energy, which was determined by calculating the apparent rate of heat release as derived from RCM high speed pressure data. A lean limit for 90% chemical energy conversion was found to correspond to an equivalence ratio of 0.47 ($T_{comp} = 782$ K). Schlieren photography was employed as a diagnostics tool to visualize the flame initiation and propagation inside the RCM.

Keywords: Laser ignition; Rapid Compression Machine; Schlieren imaging; Natural gas

1. Introduction

Recent advances in laser technology and fiber optic spark delivery systems are contributing to an increased interest in practical laser ignition systems [1,2]. Several research groups have investigated the feasibility of replacing traditional electrical spark plug systems used in internal combustion engines with laser ignition systems [3–6]. Experimental results indicate many potential advantages over conventional ignition systems, including greater control over the location and timing of the ignition kernel inside the engine. Also, due to its electrodeless configuration, it eliminates problems such as spark plug erosion (present especially at high pressures) and reduces the possibility of flame quenching due to heat loss through the electrodes. Finally, because

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of the different mechanism of plasma formation, laser induced breakdown has been shown to lead to higher plasma temperatures than conventional sparks. All of the aforementioned advantages can potentially contribute to leaner engine operation with reduction in NOx formation [7], higher pressure engine operation, and more reliable hardware systems.

In general, there are four modes of laser ignition as described by Ronney [8]: non-resonant breakdown, resonant breakdown, thermal ignition and photochemical ignition. The last three methods generally require wavelength-specific laser sources making their practical implementation more challenging. Our current study focuses on the widely used non-resonant breakdown approach using an Nd:YAG laser ($\lambda = 1064$ nm). Non-resonant breakdown is achieved by tightly focusing a high power laser beam to intensities allowing optical breakdown of the gas molecules ($I \sim 300$ GW/cm^2 [9], where I is the laser pulse intensity) and plasma formation. The main mechanisms that govern the plasma formation are: multiphoton ionization (MPI) that leads to formation of initial free electrons and electron avalanche ionization (EAI) in which the free electrons are accelerated through inverse bremsstrahlung to generate further ionization by collisions with gas molecules. This technique is also the most similar to the classical capacitive discharge ignition (CDI); however, it possesses the distinct advantage that the breakdown intensity reduces as pressure increases [10].

The present research seeks to address a gap in the literature for high temperature and pressure combustion data by studying laser-induced spark ignition of methane–air mixtures in the engine-like conditions provided by the Rapid Compression Machine (RCM). In particular, we are investigating the physics of laser ignition by conducting a study of minimum spark energy (MSE) and minimum ignition energy (MIE). The lean-limit of methane–air mixtures under laser ignition is also investigated experimentally.

The minimum ignition energy is a fundamental parameter for combustion. As described by Lewis and Von Elbe [11], if insufficient energy is deposited inside a small ignition volume (for example in the form of a plasma kernel generated using a laser), the produced radicals recombine more quickly than they are generated through chain branching reactions and the heat is conducted away from the surface of the kernel. This leads to flame quenching after only a small fraction of the reactants have been consumed. Alternatively, if the delivered energy is above a certain threshold, then heat is generated inside the ignition kernel faster than it is lost due to conduction in the unburned gas. In this scenario, the ignition kernel transitions into a steady premixed flame, which propagates throughout the combustible mixture and completely consumes the reactants. The stochastic nature of laser ignition, in particular minimum spark energy (MSE) and minimum ignition energy (MIE), has been observed by several research groups. For example, Choi et al. [12] reported a variation in the probability of creating sparks as laser pulse energy was varied. Probability of 100% was only observed after the laser intensity was ~50% larger than what was required to create sparks with minimum probability. Strozzi et al. [13] showed that the percentage of successful ignition events varies with laser pulse energy and the variation is most significant at leaner conditions. For the current study, we have separated the MSE from MIE by choosing appropriate test conditions to describe both with a statistical approach.

Lean limits for laser ignited methane–air system have been reported in literature. For example, Weinrotter et al. [14] were able to ignite methane–air mixtures as lean as $\Phi = 0.52$, while Gupta et al. [15] noted a lean limit of $\Phi = 0.5$ under laser ignition (compared to $\Phi = 0.6$ from a conventional capacitive discharge ignition system). One of the first laser-ignition studies on methane–air conducted by Phuoc and White [16] found a lean limit corresponding to an equivalence ratio of $\Phi = 0.66$. In this study we are reporting the successful ignition of mixtures as lean as $\Phi = 0.4$. While this is lower than has been observed by other research groups, it should be noted that observed lean limit strongly depends on the initial conditions of the fuel–air mixture (i.e. temperature, pressure, flow field).

2. Experimental setup

2.1. Rapid Compression Machine

The Colorado State University (CSU) RCM is an opposed piston system designed and built by Marine Technology, LTD of Galway, Ireland [17–19]. The CSU RCM, shown schematically in Fig. 1, can operate with compression ratios ranging from 10:1 to 14:1 and can reach maximum compressed pressures (P_{comp}) up to 50 bar. The compression process occurs in approximately 20 ms depending on the initial pressure of the gaseous mixture. Typically, RCM experiments are employed to produce autoignition without an external ignition source. In RCM autoignition experiments, initial conditions are typically selected such that the fuel-oxidizer mixture autoignites within 5–200 ms after the end of compression allowing ignition delays to be measured from pressure traces. Ignition delay measurements, together with modeling, can be used to validate chemical kinetic mechanisms. For the purpose of this research, the RCM was integrated with a laser system to initiate ignition of the combustible mixture at a specified time interval after compression using a laser generated spark. Experiments were conducted at a compression ratio of 11.6:1. The initial pressure and temperature as well as the

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