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Evolution of flame-kernel in laser-induced spark ignited mixtures: A parametric study

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ABSTRACT

The present work focuses on the early stages of flame-kernel development in laser-induced spark ignited mixtures issuing out of a Bunsen burner. The time-scale of 3 μs to 1 ms associated with the flame-kernel evolution stage of an ignition event is targeted in this work. A CH_4/air mixture (equivalence ratio $\phi = 0.6$) is studied as a base case, and compared with CH_4/CO_2/air (mole fractions = 0.059/0.029/0.912, respectively) and CH_4/H_2/air (mole fractions = 0.053/0.016/0.931, respectively) mixtures for nearly the same adiabatic flame temperature of 1649 K. The spatio-temporal flame-kernel evolution is imaged using planar laser induced fluorescence of the OH radical (OH-PLIF), simultaneously with H-alpha emission from the plasma. The H-alpha emission suggests that the plasma time-scale is well below 1 μs. The PLIF images indicate all the stages of kernel development from the elongated kernel to the toroidal formations and the subsequent appearance of a front-lobe. The different time-scales associated with these stages are identified from the rate of change of the kernel perimeter. The plasma is followed by a supersonic kernel-perimeter growth. Larger flame-kernel spread is found in the case of CH_4/H_2 mixtures. A distinct shift in the trends of evolution of LIF intensity and kernel perimeter is observed as the fuel concentration is varied near the lean flammability limit in CH_4/air ($\phi = 0.35$–0.65) and H_2/air ($\phi = 0.05$–0.31) mixtures. The flow velocity (Reynolds number, *Re*) effect in both laminar and turbulent flow regimes ($Re = \sim 600$–6000) indicates that the shape of the flame-kernel changes at higher velocities, but the size of the kernel does not change significantly for a given time from the moment of ignition. This could be due to a balance between two competing effects, namely, increase in the strain rate that causes local extinction and thus decreases the flame-kernel growth, and increase in the turbulence levels that facilitates increased flame-kernel surface area through wrinkling, which in turn increases the flame-kernel growth.

1. Introduction

The combustion process is generally triggered by an external source of energy through ignition. Ignition is defined as the transformation of combustible reactants from a nonreactive state to a self-sustained reactive state without further contribution from an ignition source [1]. This definition highlights the significance of the ignition event for reliable operation in practical devices. Over several decades, ignition has been dominated by electric-spark igniters in practical devices such as spark-ignition engines and gas turbines. A comprehensive review of spark-ignition in turbulent non-premixed flames is provided by Mastorakos [2]. Since the advent of lasers in the 1960 s, numerous researchers have exploited them to generate spark. Ever since the early work of Ramsden and Savic [3] on laser-induced spark in air, numerous researchers have investigated this phenomenon.

Laser ignition phenomena are reviewed by Ronney [1], who provided comparison to the classical electric-spark. Laser ignition mechanisms are classified into four categories [1,4]. A *thermal initiation* takes place when the solid target is heated by a laser source, which in turn acts as an ignition source without electrical breakdown. A *resonant breakdown* requires a close wavelength match to photo-dissociate a particular target species that in turn initiates electrical breakdown. A *photo-chemical dissociation* occurs when a target molecule is dissociated at a certain wavelength. A dissociated radical initiates chain reaction, and thus ignition commences without any breakdown. A *non-resonant breakdown* can be realized at any

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wavelength when the deposited energy density exceeds the breakdown threshold. This process is initiated by seed electrons released from an impurity (dust, aerosol or soot-particles) in the gas upon absorption of photons [5]. The seed electrons accelerate in the induced electric field, which is referred as inverse bremsstrahlung [6]. This in turn generates more electrons from the gas molecules [7], which eventually leads to an avalanche of electrons [1,5]. This non-resonant breakdown mode of ignition has been widely studied, as the wavelength dependence on the breakdown process is not significant [8,9], and thus readily available Nd:YAG lasers can be employed. The pulse energy requirement for non-resonant breakdown is much more than the other three modes of laser ignition [1], yet it is small enough (a few mJ to tens of mJ) for implementing in practical devices. The non-resonant breakdown is also referred to as the laser-induced spark (LIS) ignition. Further details on these four modes of laser ignition can be found in review articles [1,7].

The benefits of laser ignition as compared to the traditional electric-spark ignition have been highlighted by a few authors [1,7,10,11]. The rate and amount of energy deposition can be precisely controlled with laser ignition. Ignition timings can be controlled accurately owing to faster time scales than electric-spark. Additionally, the ignition location can be directed at a favorable region in a combustion chamber. In a fuel-lean mixture, the burn time can be shortened by igniting the mixture at predetermined multiple locations, as demonstrated by [12]. The use of lasers in spark-ignition engines is reported to reduce the frequency of misfiring [13,14]. At higher pressures, as in spark-ignition engines or gas turbine combustors, a spark-plug requires higher voltage potential for reliable ignition [7]. However, the higher voltage could reduce the life of the spark-plug. On the other hand, the energy requirement for LIS reduces with pressure [15]. These advantages motivate researchers to investigate LIS ignition.

Despite these advantages, laser ignition has not yet been used in practical devices such as spark-ignition engines or gas turbines. The major difficulty is the larger size of the laser source relative to the compact spark-plugs. This problem is being progressively solved by use of a compact passively Q-switched Nd:YAG and Cr:YAG lasers, similar to the work of Tsunekane et al. [16]. Although it is reported that the laser ignition could ignite a fuel-lean mixture (within the flammability limit) that cannot be easily ignited with spark-plugs [17,18], the minimum ignition energy required for laser ignition at atmospheric pressure is usually more than that of the electric-spark [19–23]; however, towards lean and rich flammability limits, the differences in the minimum ignition energy are less pronounced [21]. Ignition with the electric-spark is believed to be assisted with the catalytic contribution from the electrodes [8], whereas LIS is free from such electrodes. Additionally, the energy absorbed by the spark in the LIS process is partly lost to the shock-waves [19,24]. The higher energy requirement of LIS is not a major concern [1], as these energy levels (a few tens of mJ) could be achieved with available laser sources.

Thus, laser ignition has potential applications in spark-ignition engines and gas turbines. A continuous or pulsed laser ignition method is proposed to replace the flame-holders in air-breathing propulsion devices. It is argued that the use of a laser source instead of a physical object to hold the flame could avoid the pressure loss across the flame-holders. Such an application has been demonstrated even in a hypersonic scramjet engine [25]. However, this study suggests a pulse energy requirement of 750 mJ at 100 kHz repetition rate to hold the flame continuously. Such significant requirement for supersonic flow could only be met with bulky lasers at the present level of technology, which makes the use of LIS difficult in such applications. In such scenarios, other modes of laser ignition, namely resonant breakdown or photochemical dissociation, may be applied, where the energy requirement is substantially lower than that for non-resonant breakdown.

The physical mechanisms of the ignition event starting from the laser pulse to the propagating flame front has been has been investigated by quite a few researchers [10,19,21,24,26]. The ignition process consists of a sequence of processes, eventually leading to a propagating flame. These processes include plasma formation followed by shock-waves, flame-kernel development, and eventually propagating flames. Each of these processes is identified with their respective time-scales [11,27]. A typical time-scale of flame-kernel development is 1–1000 μs [11,27]. This critical event governs the ultimate fate of the ignition process [24]. The literature related to LIS ignition indicates that information regarding the early stage of ignition and the effect of various key parameters is scarce. Therefore, it is worthwhile to investigate the flame-kernel behavior systematically using advanced laser diagnostics, which in turn could provide further insight and database for model validation.

The LIS ignition studies at atmospheric pressure in unconfined configurations are also reported by numerous researchers [10,21,24,26,28]. The experimental configurations designed for atmospheric pressure are relatively simple. Thus in the present work, we choose the Bunsen burner configuration.

The objective of the present work is to investigate the flame-kernel development of LIS ignited mixtures of various gas compositions under different flow regimes. The flame-kernel is imaged using planar laser induced fluorescence of OH (OH-PLIF). Simultaneously, H-alpha emission from the plasma is also recorded. The flame-kernel in a CH_4/air mixture is spatially and temporally resolved at certain time steps (1–1000 μs) as a base case. The effect of energy of the ignition-laser is investigated. The flame-kernel characteristics near the lean flammability limit (LFL) are investigated in CH_4/air as well as in H_2/air mixtures as a function of fuel concentration. The ignition of the CH_4/air mixture is compared with that of CH_4/CO_2/air and CH_4/H_2/air mixtures for a given adiabatic flame temperature. The choice of composition of these multi-component fuels is motivated by a typical composition of biogas (CH_4/CO_2) and syngas ($CH_4/CO_2/H_2$), which are potential alternative fuels. Additionally, the effect of reactant velocity (and indirectly, turbulence level) on flame-kernel is studied in CH_4/air mixtures.

The fundamental knowledge of the ignition process in a simple experimental configuration acts as a milestone towards our understanding of LIS ignition process in practical high-pressure devices, such as spark-ignition engines and gas turbine combustors. Additionally, the database generated in the present work for a wide variety of conditions can be used to validate numerical simulations of the flame-kernel development.

2. Experimental details and data reduction procedure

2.1. Burner

In most of the past works [8,11,12,19,22,27,29,30], a constant volume combustion vessel has been used, where the mixture is essentially quiescent. In the present work, on the other hand, a Bunsen burner of 10 mm diameter is employed, similar to Beduneau et al. [10,21]. A Bunsen burner operated at atmospheric pressure offers significant simplicity, as there are no optical windows required, which in turn avoids complexity in the experimental set-up. Spiglanin et al. [24] too ignited flowing reactants, but on a McKenna burner. The McKenna burner configuration was also used by Chen and Lewis [26] to visualize laser-induced breakdown and ignition. In the present work, air and fuel are premixed and then issued through the burner at a certain velocity (typically 90 cm/s). For a given combination of equivalence ratio and bulk velocity, the flow rates are predetermined. A number of mass flow meters are used to cover the wide range of gases and flow rates. The air and CH_4 flow rates are metered with thermal flow meters (Vögtlin Instruments) and controlled through high precision needle valves. The flow rates of H_2 and