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Stabilization of a premixed methane-air flame with a high repetition nanosecond laser-induced plasma

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ABSTRACT

Laser-induced plasma ignition has been applied in various combustion systems, however, work on flame stabilization with repetitive laser-induced plasma (LIP) is rather limited. In this paper, stabilization of a premixed methane-air flame with a high repetition nanosecond LIP is reported. The plasma energy coupling and the temporal evolution of the flame kernels generated by the LIPs are investigated with different laser repetition rates, i.e., 1 Hz, 100 Hz and 250 Hz, respectively. The plasma energy coupling is not affected in the air flow and in the premixed methane-air flow with the applied laser repetition rates. Continuous combustion flame stabilization has been achieved with LIPs of 100 Hz and 250 Hz, in terms of catch-up and merging of the consecutive flame kernels. The flame kernel formed by the last LIP does not affect the evolution of the newly formed flame kernel by the next LIP. The catch-up distance, defined as the distance from the LIP initiation site to the flame kernel catch-up position, is estimated for different laser repetition rates based on the temporal evolution of the flame kernels. A higher laser repetition rate will lead to a shorter catch-up distance which is beneficial for flame stabilization. The up limit for the laser repetition rate to realize effective flame stabilization is determined from the critical inter-pulse delay defined from the onset of the LIP to the return of the initially contraflow propagating lower front to the LIP initiation site. The up limit is 377 Hz under the flow conditions of this work (equivalence ratio of 1, flow speed of 2 m/s, and Reynolds number of 1316).

1. Introduction

Ignition and flame stabilization are important issues in many combustion systems. Reliable ignition and effective flame stabilization are essential for stable, smooth and safe operation of the combustion systems. In the last two decades, laser-induced plasma ignition (LIPI) has been investigated extensively with its many benefits for combustion systems [1–10]. The location of the laser-induced plasma (LIP) can be easily adjusted using appropriate steering and focusing optics. The ignition timing and energy deposition are more flexible in the LIPI than the conventional electric spark plugs [7,9]. Meanwhile, the heat loss from the flame kernel to the electrodes in the electric discharge ignitions can be avoided in the LIPI [7,9] , which is beneficial for the initial flame kernel survival and development. Furthermore, the electromagnetic compatibility of the LIPI system is better than the electric spark plugs [11]. With such advantages, the LIPI has been investigated in various combustion systems, including premixed and non-premixed lab-scale burners [1,2,10,12–14], natural gas engines [15], internal combustion engines [16,17], gas turbines [18], model rocket engines [11,19–21] and scramjet engines [22–25]. The ignition parameters (including minimum ignition energy, ignition delay, etc.) [2,10,12,13], flame kernel dynamics [1,3,8,26,27], and factors affecting the final ignition results [1,12] have been investigated.

A development of the LIPI is laser-induced plasma-assisted combustion (LIPAC). Plasma-assisted combustion (PAC) is a technique to improve combustion behaviors with various plasmas serving as thermal or (and) radical sources [28–30]. In the last years, shortened ignition delay, extended flammability limit and enhanced flame stability have been achieved using this technique [28–33]. The LIPAC has inherited all the merits of the LIPI over the electric discharge plasmas. Meanwhile, the LIPAC is non-intrusive and can eliminate the pressure losses caused by the conventional flameholders [34]. The concept of LIPAC was proposed by Medoff and McIlroy [34], who investigated flame stabilization using a 15–20 Hz nanosecond (ns) Nd: YAG laser-induced plasma in a supercritical subsonic premixed methane-air flow with a flow speed of 1.10 m/s. The temporal evolution of the flame kernels generated by the LIPs was investigated using the CH* chemiluminescence imaging method. Catch-up of the

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flame kernels generated by the consecutive LIPs was demonstrated. However, the *catch-up distance*, defined as the distance from the LIP to the position where the flame kernel catch-up and continuous combustion was achieved, was in the order of several centimeters, which led to strong instabilities in the flame base. In last years, our group have investigated LIPAC using a 1 kHz femtosecond (fs) LIP. Premixed $CH_4/O_2/N_2$ flames with flow speed up to 5 m/s were stabilized by the fs LIP [35]. The flame propagation speed of a laminar premixed $CH_4/O_2/N_2$ flame attached to the burner tube rim was improved by 5.3–30.8% with the fs LIP serving as the radical provider in the fresh flow below the flame front [36]. However, since the fs laser system is complex, large in dimension and not suitable for practical applications, more compact high repetition ns laser system is preferred in the LIPAC investigations. The ns LIP differs from the fs LIP in both breakdown mechanism and plasma properties, thus the LIPAC mechanism and properties will also differ greatly. Therefore, further work needs to be done on the ns LIPAC. In a recent work, Bak et al. [37] mimicked high repetition LIPI using two successive ns laser pulses with adjustable inter-pulse delays. Catch-up of the successive flame kernels was demonstrated, however, sustainable flame stabilization was not achieved due to the limited number of the laser pulses. In previous work, we investigated LIPAC of premixed methane-air flames with a ns Nd: YAG laser with a repetition rate of 50–100 Hz [27,38]. Quasi-stable combustion was achieved under natural blow-off conditions with both direct gas breakdown plasma [38] and laser ablation plasma [27]. However, the flame base still suffered fluctuations due to the large catch-up distances in the order of tens of millimeters. Therefore, to achieve more stable combustion, even higher laser repetition rate is required. Meanwhile, although the evolution of a single flame kernel in the LIPI process has been investigated [1,3,8,26], detailed work on the evolution of the flame kernel in the presence of the last flame kernel in the high repetition LIPAC process is rare [34,37]. The question whether the existing last flame kernel will affect the evolution of the newly generated flame kernel remains unanswered.

In this work, we report stabilization of a premixed methane/air flame with a high repetition ns LIP generated by a Nd: YAG laser. Firstly, the plasma energy coupling in the air flow and in the premixed methane-air flow is investigated and compared with different laser repetition rates. Then, the temporal evolution of the flame kernel generated by a single LIP and the consecutive flame kernels by high repetition LIPs is investigated using the CH* chemiluminescence imaging method. Flame stabilization in terms of catch-up of the consecutive flame kernels is achieved using high repetition LIPs. The effect of the existing flame kernel formed by the last LIP on the evolution of the newly formed flame kernel is analyzed by comparing the temporal propagation of the new flame kernel in the absence and presence of the existing flame kernel. Finally, the catch-up distances corresponding to different laser repetition rates and the up limit for the laser repetition rate to achieve effective flame stabilization are estimated from the temporal evolution of the flame kernels.

2. Experimental setup

Shown in Fig. 1 is the schematic of the experimental setup for stabilization of the premixed methane-air flame with the high repetition LIP. A quartz tube burner with an inner diameter of 10 mm, an outer diameter of 12 mm, and a length of 200 mm was used for the flame stabilization investigation. Pure methane and compressed dry air were premixed in a mixing chamber and then fed into the burner tube. The equivalence ratio (Φ) and flow speed (v_g) of the premixed flow were adjusted using two mass flow controllers (MFCs, MC serials, Alicat). The accuracy of the MFCs was claimed to be better than 2% by the producer. The premixed flow was set to the stoichiometric condition (Φ=1). The v_g was fixed to 2 m/s and the corresponding Reynolds number (*Re*) was 1316. The flame could not be self-stabilized on the burner tube under such flow conditions.

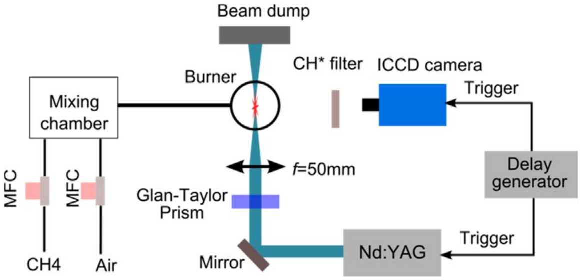

Fig. 1. Experimental setup for flame stabilization with the high repetition laser-induced plasma.

The 1064 nm, ~10 ns output of a house-developed laser-diode pumped, Q-switched Nd: YAG laser was applied to generate the plasma for flame stabilization. The laser was focused onto the axis of the burner tube, 5 mm above the burner tip, using a short focal length (*f*=50 mm) plane-convex BK7 lens. Three repetition rates were applied in this work, i.e., 1 Hz, 100 Hz and 250 Hz, respectively. The laser pulse energy was adjusted using a Glan-Taylor prism. The *plasma energy*, i.e., the energy coupled into the plasma during the breakdown process, was measured as the difference of the incident laser energy and the residual energy following the breakdown [2, 10, 12, 13]. When the laser worked at 1 Hz, the incident laser pulse energy and the residual energy were measured using a joule meter (J-50MB-HE, Coherent). When the laser worked at 100 Hz and 250 Hz, the corresponding values were determined by measuring the average power with a laser power sensor (919P-040–50, Newport).

To evaluate the stability of the flames obtained using the repetitive LIPs, and to investigate the evolution behaviors of the newly formed flame kernel (denoted as K_{new} in the following context) in the absence and presence of the existing flame kernel formed by the last LIP (denoted as K_{exist} in the following context), the temporal evolution of the flame kernels was investigated using the CH* chemiluminescence imaging method [34,37]. The A-X CH* emission of the flame kernels around 431 nm was imaged using a high speed intensified CCD (ICCD) camera (HSFC, PCO) coupled with a 105 mm F/4.5 UV lens (CoastalOpt). To selectively image the CH* emission, a bandpass filter (BrightLine FF01-427/10, Semrock) centered at 427 nm with a bandwidth of 20 nm was placed in front of the UV lens. The temporal evolution of the flame kernel generated following a single LIP (with the laser working at 1 Hz) and consecutive flame kernels generated by high repetition LIPs (with the laser working at 100 Hz and 250 Hz) was investigated and analyzed. The whole experimental system was synchronized with a digital delay generator (DG645, Stanford Research Systems). The delay generator provided the external triggers for the Nd: YAG laser and the ICCD camera.

3. Results and discussion

3.1. Plasma energy coupling in the air flow and in the premixed methane-air flow

The plasma energy is an important factor for the laser-induced plasma ignition (LIPI). Investigations on the factors affecting the ultimate LIPI results show that, a higher plasma energy tends to result in higher concentrations of combustion radicals and lead to final successful self-sustainable ignition [1,12]. In the high repetition breakdown process, the plasma energy coupling may be reduced, if the laser pulse falls into the temporal region within which the hydrodynamic and thermal expansion due to blast wave propagation and combustion process lead to reduction of gas density and increase of breakdown threshold [27,37]. To determine whether the plasma energy coupling will be affected in the high repetition LIPI process, the plasma energies of the breakdowns both in the air flow and in the premixed methane-air