Combustion and Flame 193 (2018) 471–480

Contents lists available at ScienceDirect

Combustion and Flame

journal homepage: www.elsevier.com/locate/combustflame

Reduction of flame development time in nanosecond pulsed high frequency discharge ignition of flowing mixtures

Joseph K. Lefkowitz[1,*], Timothy Ombrello

U.S. Air Force Research Laboratory (AFRL/RQHF), 1950 Fifth Street, Building 18, Wright-Patterson AFB, OH 45433, USA

A R T I C L E I N F O

Article history:
Received 5 July 2017
Revised 28 August 2017
Accepted 5 April 2018

Keywords:
Ignition
Plasma assisted combustion
Non-equilibrium plasma
Spark ignition
Flame development time

A B S T R A C T

The effects of discharge and flow parameters on ignition kernel development time are explored in flowing methane–air mixtures. A nanosecond pulsed high frequency discharge in a pin-to-pin configuration is used as the ignition source, providing 2.9 ± 0.23 mJ/pulse. The effects of pulse repetition frequency (PRF) in the range of 10–300 kHz, number of pulses in the range of 1–50 (≈2.9–145 mJ), equivalence ratio in the range of 0.55–0.65, gap distance in the range of 0.5–2.5 mm, and flow velocity in the range of 2.5–10 m/s are explored. For all conditions, the ignition events are in the "fully-coupled" regime, in which high ignition probability is achieved and locally extinguished ignition kernels are avoided. It is found that reducing the PRF reduces the kernel development time for fixed total energy deposition due to an increased volume of unburned mixture exposed to the discharge. Increasing the number of pulses at a given PRF also decreases the kernel development time, again by increasing the volume of gas exposed to the discharge. The equivalence ratio only has an effect on the kernel growth rate after the discharge, with identical kernel areas measured at all equivalence ratios while the discharge is active. Increasing gap distance decreases the kernel development time by providing a larger initial kernel volume as well as reducing heat and radical quenching at the electrode surfaces. Finally, the flow velocity has an effect on the kernel growth rate at velocities greater than 5 m/s, with larger flow velocities resulting in shorter kernel development time. This is due to the competing rates of self-propagating flame expansion and kernel growth due to convection past the discharge region. The combined effects of all of the above parameters on the kernel area after the discharge are summarized in a correlation equation, which predicts the trends in kernel growth rate based on an estimated plasma area defined by the discharge duration, flow velocity, and gap distance.

1. Introduction

Ignition by nanosecond pulsed high frequency discharges (NPHFD) has the potential to extend ignition limits and reduce ignition times in a variety of applications, from internal combustion engines [1–4] to scramjets [5–7]. Real engines all involve some degree of fluid motion, which interacts with the discharge and developing ignition kernel, and to a large extent determines the minimum ignition energy (MIE) and the flame development rate [8]. The degree of fluid motion is highly dependent on the engine type, with IC engines having 1–10 m/s bulk flow velocity [9], gas turbines having 10–100 m/s flow velocity in swirl-stabilized combustors [10], and scramjet cavity recirculation zones having as high as 100 m/s flow velocity [11–14]. In some of these environments, the flow residence time in the engine may be on the same order as the ignition and kernel development time, particularly for engines operating with lean fuel/air mixtures, those with high-speed flows, or those requiring ignition at low temperature (i.e. high altitude ignition). In these cases, the rate of early kernel growth is critical for ignition success and completion of combustion.

Our previous study in flowing methane/air mixtures sought to quantify the effects of discharge and flow parameters on ignition probability using NPHFD [15] in the spark regime [16,17], in which the inter-pulse time (τ, inverse of the pulse repetition frequency, PRF), number of pulses (N), flow velocity (U), gap distance (D), and equivalence ratio (φ) were varied independently and the probability of ignition was determined. It was found that three ignition regimes exist for NPHFD ignition, depending primarily on the inter-pulse time. At short inter-pulse times ($\tau < 1 \times 10^{-4}$ s for approximately 3 mJ/pulse and in 10 m/s flow), the fully-coupled regime is characterized by the highest ignition probability and ignition ker-

* Corresponding author.
E-mail address: joseph.lef@technion.ac.il (J.K. Lefkowitz).
[1] Present address: Faculty of Aerospace Engineering, Technion – Israel Institute of Technology, Technion City, Haifa 3200003, Israel.

https://doi.org/10.1016/j.combustflame.2018.04.009

nels which experience little local quenching. The partially-coupled regime occurs at longer inter-pulse times ($\tau \approx 1 \times 10^{-4}$–$5 \times 10^{-4}$ s) and is characterized by the lowest ignition probability and ignition kernels which interfere destructively, leading to localized quenching and thus the lowest ignition probability. The decoupled regime occurs for all inter-pulse times longer than in the partially-coupled regime. The ignition probability is the product of the single pulse ignition probability and *N*, and is characterized by ignition kernels which do not interact with each other until significantly far downstream of the spark gap. These different degrees of inter-pulse coupling and their associated probabilities can be manipulated by the other flow parameters, particularly the gap distance and flow velocity. The competition between the time scales of electrical energy deposition and chemical heat release, conductive and convective heat loss to the electrodes and flow field, and the rate of kernel growth and movement of the kernel away from the discharge gap all contribute to the ignition probability.

This work aims to take the analysis of NPHFD ignition one step further by quantifying the development rate of the ignition kernel. This is the second metric, other than ignition probability in a given flow, which determines the success of ignition in limited residence time environments, and thus must be optimized to fully realize the benefits of NPHFD ignition. For this purpose, a well-defined flow field is provided with a velocity range of 2.5–10 m/s, and a pin-to-pin electrode configuration with adjustable gap distance is supplied discharge pulses of inter-pulse times as short as $\tau = 3.4 \times 10^{-6}$ s and with approximately 3 mJ/pulse. The current study explores the effects of inter-pulse time, number of pulses, equivalence ratio, gap distance, and flow velocity on the kernel growth rate, and aims to discover the phenomena governing the kernel growth rate as well as defines an optimization strategy for NPHFD ignition.

2. Experimental methods

2.1. Flow tunnel facility

The experimental setup has been described in elsewhere [15], and is only briefly discussed here. The tunnel consists of a constant area cross-section with dimensions of 3.81 cm by 3.81 cm. The premixed methane/air flow is introduced at one end of the tunnel via calibrated mass flow controllers with measured uncertainties of ±2% of the flow setting, and passes through three screens separated by 1.27 cm with mesh sizes chosen for the gas velocity range to provide a uniform flow. Static pressure in the tunnel was maintained at approximately 100 kPa and the initial temperature at approximately 295 K (ambient room conditions) for all experiments. There are two 1.6 mm diameter lanthanated tungsten electrodes located 5.18 cm downstream of the screens in a pin-to-pin geometry (sharpened to a 10° half angle cone) which can be moved independently with micrometers to change the gap distance.

Optical access is maintained on two opposite sides (UV grade fused silica), starting upstream of the electrodes, allowing for high-frame-rate schlieren to capture the global ignition process. A continuous light source (Hg-Xe lamp) was used for illumination of the test section, two spherical mirrors collimated and refocused the light on a knife edge, and a Photron SA-Z camera was utilized to take images at up to 40,000 frames/s with an exposure time of 2.5 µs. The imaging resolution was 0.15 mm/pixel using a 105 mm focal length lens.

To evaluate the local flow conditions in the discharge region, hot wire anemometry measurements were performed at a distance 4 mm downstream of the electrode location. Measurements were made with and without the presence of the electrodes. A plot of the unperturbed velocity profiles (without electrodes) is shown in Fig. 1a. It was found that the local flow velocity in the center of the tunnel is significantly greater than the bulk flow velocity calculated using the volumetric flow rate. For the 2.5 m/s, 5 m/s, and 10 m/s conditions, the average local flow velocity in the center region of the tunnel was measured to be 3.75 m/s, 7.25 m/s, and 12.5 m/s, respectively. The turbulent intensity was measured to be between 0.3 and 0.5%. The velocity discrepancy is likely due to the reduced velocity in the boundary layer region and in the corners of the tunnel. With the electrodes present, a significant wake region was measured, affecting the flow velocity and turbulence levels directly downstream of the electrodes. A plot of the perturbed flow profiles (with electrodes) is provided in Fig. 1b, using a 2 mm electrode gap distance. At the measurement location, the velocity was reduced by a maximum of 65% and the turbulent intensity rose to 10–25%. However, the velocity and turbulent intensity directly downstream of the electrode gap were affected minimally. The presence of the wake should continue to perturb the flow as far as 100 mm downstream of the electrodes. Kono et al. [18] observed that in propane–air mixtures at similar flow conditions the electrodes had an effect on both the MIE and the dynamics of ignition growth, and that this effect could be reduced by increasing the gap distance and decreasing the electrode diameter. Further studies will be needed to fully characterize the wake region and its effects on ignition kernel growth dynamics.

2.2. NPHFD system

For the pulsed power source, a custom exciter from Transient Plasma Systems (TPS) was used. The exciter produces approximately 10 ns FWHM pulses at a maximum pulse repetition frequency of 300 kHz for up to 500 pulses. The peak voltage is a function of load, with a maximum of 10 kV into a 50 Ω resistor, and 15 kV recorded for a 2 mm discharge gap in air at a temperature of 295 K and pressure of approximately 100 kPa. The peak voltage setting was held constant for all experiments. Energy measurements were performed with a custom in-line voltage probe and current monitor from Transient Plasma Systems. The voltage and current waveforms were recorded with a 1 GHz oscilloscope (Teledyne LeCroy, Model HDO6104).

The energy is computed using the formula: $\varepsilon = \int IV dt$, where I is current, V is voltage, and ε is the energy deposited during a single discharge pulse. Special care was taken to properly account for time delays between the voltage and current waveforms, as well as to measure the displacement energy, which was found to be a negligible contribution to the total energy. Sample voltage, current, and energy deposition waveforms were provided in our previous work [15], as well as measurements of energy deposition at different flow and discharge conditions. It was found that energy per pulse is 2.9 ± 0.23 mJ for all experiments, and the energy did not vary throughout a burst of pulses except for the first pulse, which deposited 0.4 mJ less energy than all subsequent pulses. The energy per pulse was a weak function of inter-pulse time, with slightly higher average energy per pulse as the inter-pulse time is reduced, reaching a maximum of 3.2 ± 0.26 mJ for $\tau < 1 \times 10^{-5}$ s. The energy per pulse was not found to vary within experimental uncertainty as any of the other parameters explored in this study were varied. To ascertain whether the variance in energy with inter-pulse time had a significant effect on ignition, a set of experiments in which the peak voltage was reduced as the inter-pulse time was reduced in order to maintain constant energy per pulse was carried out. No differences in flame growth rate or ignition probability were measured within experimental uncertainty [15].

2.3. Kernel growth measurements

The kernel area was extracted from the schlieren imaging using an in-house edge tracking program designed in MATLAB and based