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An exploration of inter-pulse coupling in nanosecond pulsed high frequency discharge ignition

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ABSTRACT

A parametric exploration of the dynamics of ignition using nanosecond pulsed high frequency discharges (NPHFD) in flowing mixtures of methane and air is conducted to determine the “inter-pulse coupling” effect of a burst of high frequency discharges in the pulse repetition frequency (PRF) range of 1–300 kHz. The impacts of PRF, number of pulses, equivalence ratio, discharge gap distance, and flow velocity are quantified in terms of ignition probability and minimum ignition power, and schlieren images of ignition kernel development are presented. Three regimes of inter-pulse coupling are found for different values of PRF: fully-coupled, partially-coupled, and decoupled. Each regime is characterized by distinct ignition probabilities and kernel structures. The fully-coupled regime occurs for the highest PRF and exhibits complete ignition of the kernel and the highest ignition probability. The partially-coupled regime occurs for intermediate PRF and exhibits only local ignition of portions of the kernel and has the lowest ignition probability. The decoupled regime occurs for the lowest PRF and exhibits multiple non-interacting ignition events with ignition probability being a linear function of the number of pulses. The effect of equivalence ratio is found to increase or decrease the ignition probability without altering the structure of inter-pulse coupling. The electrode gap distance determines the degree of heat and active species quenching to the electrode surfaces, and shifts the transition between the partially-coupled and fully-coupled regimes to higher PRFs as the gap distance is decreased. Flow velocity determines the degree of convective heat loss, with lower velocities increasing the ignition probability and altering the structure of inter-pulse coupling in a non-monotonic fashion.

1. Introduction

The success of localized discharge ignition in engine environments is a function of a range of parameters of the flow environment, plasma discharge, and electrode geometry. The local flow conditions significant to ignition include the reactivity of the mixture, pressure, initial temperature, flow velocity, turbulence intensity and scale, thermal capacitance, and diffusive heat and mass transfer rates of the gas. Each can have an effect on the minimum ignition energy (MIE) [1–6]. The plasma parameters of importance include the energy deposition rate, total discharge time, and magnitude of the electric field [7–10]. Together, these will determine the total energy deposition, plasma volume, temperature (electronic, rotational, vibrational, translational), and species concentrations in the plasma. Finally, the electrode gap geometry and material play a role in determining the rate of heat and radical quenching on the electrode surfaces, the electric potential required for gas breakdown, and the distribution of the electric field. In considering the optimization of ignition for a given system, all of the aforementioned factors must be taken into account to ensure repeatable ignition while minimizing inefficiencies and wear on the electrodes.

For quiescent mixtures, optimization of the plasma discharge and dynamics of ignition kernel formation have been considered in depth [2–9,11]. In the work of Maly and coworkers [11–13], a range of discharge types were implemented, and it was concluded that the optimal discharge device should deposit the energy needed for ignition in the shortest possible time using a fast rise of the voltage waveform. Thus, most of the energy is channeled into the breakdown stage of the discharge, producing an expanding plasma volume which will reach the critical radius necessary for ignition [4–6,14] in the shortest possible time. Further studies have determined that short duration, high peak voltage discharges favorably target electronic or vibrational excitation and dissociation of gas molecules, which facilitates the initial oxidation of fuel and thus accelerates the transition into a freely propagating flame [10,15–17].

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This ideal ignition method may not extend to flowing environments, especially for cases in which the gas flow rate is greater than the propagation rate of the developing flame. In such a case, passage of gas through the discharge region creates a large volume of activated mixture without the need for rapid gas expansion or large volume discharges. Ballal and Lefebvre [1] determined that an optimal discharge duration exists in which the MIE is minimized for a given flow condition. Discharge durations shorter or longer than this time results in excessive heat loss, either to the initial shock wave or to convective heat transfer. For energy deposition rates greater than the minimum required for ignition, the passage of flow by the electrodes may offer a significant advantage in terms of ignition kernel growth rate by activating a large gas volume. This idea has been explored through the use of plasma torches for ignition of high speed flows [18,19]. While promising results have been obtained, the high power consumption of such a device renders it impractical for use in many vehicular applications. Recently, the use of nanosecond pulsed high frequency discharges (NPHFD) has been suggested as a means to maintain high electron density in a discharge for long periods of time (or continuously) without the high power requirements of DC discharges [20]. In the work of Pancheshnyi et al. [21], a discharge of 10 ns full width half maximum (FWHM), 5 kV peak voltage, 1.5 mm gap distance in a pin-to-plane configuration, and pulse repetition frequency (PRF) of 30 kHz was utilized to ignite quiescent propane-air mixtures. One of the major findings of this study was that increased numbers of pulses beyond the minimum required to ignite the mixture reduced the development time of the ignition event. A similar result was found in the work of Xu et al. [22] for quiescent propane-air mixtures at pressures of 101–1013 kPa for discharges of 10 ns FWHM, 5–10 kV peak voltage, 0.6 mm gap distance in a pin-to-pin configuration, and PRF of 1–30 kHz. It was observed that as the number of discharge pulses in a burst is increased, the size of the initial kernel is also increased due to rapid gas heating in the discharge region [15,23,24], and thus a shorter ignition time can be obtained. In addition, for matched total energy deposition and discharge power, NPHFD resulted in shorter ignition times compared to an inductive discharge device [22]. Expanding on these results, Lovascio et al. [25] explored the effect of increasing PRF on ignition in quiescent mixtures of propane-air at a pressure of 200 kPa, 30 kV peak voltage, 1.2 and 3 mm gap distances in a pin-to-pin configuration, and in the PRF range of 2–90 kHz. It was found that an optimal PRF existed which minimized ignition time for a given total energy deposition, and that increased repetition frequency beyond this point actually increased the ignition time. This result was attributed to fluid dynamic influences from the discharge which interfered with inter-pulse coupling and delayed ignition kernel development. This result was supported by direct numerical simulations of repetitive discharges revealing the mechanism by which motion is induced in the plasma [26]. Besides these investigations, there have been a number of follow-on studies exploring the physics of the NPHFD [10,15,27–29], the usefulness of NPHFD for flame-holding [30,31], and the interaction of flames or combustion chemistry with the plasma at low pressure [10, 32–37]. However, only a few studies have focused on NPHFD in flowing mixtures or in engine relevant environments [38,39].

Towards this end, in the recent study by Lefkowitz et al. [17], ignition using a NPHFD with 12 ns FWHM, peak voltage values of 9–22 kV, and PRF values of 1–40 kHz was explored in a pulsed detonation engine facility and in a flow tube at a pressure of approximately 100 kPa. It was found that both the total energy deposition and the PRF had an effect on the ignition development rate, as determined by high frame-rate schlieren imaging and pressure rise rates in the flow tube and PDE, respectively. It was determined that at low PRF (<5 kHz) the time between discharges was sufficiently long in relation to the residence time of the flow in the discharge region that multiple discharge pulses were effectively decoupled, and each acted as an independent ignition event. However, at PRF greater than 5 kHz, discharges were applied into an overlapping region, and it was observed that the flame growth rate was improved significantly. In addition, as the PRF was increased further above the minimum necessary for ignition, the flame growth rate continued to increase, signifying additional benefits to high PRF beyond the fluid dynamic interaction. This phenomenon was explained by "inter-pulse coupling" in which the heat and active species produced in one discharge pulse did not have enough time to diffuse or recombine before the following discharge pulse, leading to a buildup in both temperature and radical concentration. This phenomena had been explored in detail in NPHFD in air [40], but this work was one of the first to explore the effect of inter-pulse coupling on ignition. While the initial study proved the efficacy of NPHFD for ignition in flowing mixtures, a detailed analysis of the conditions in which inter-pulse coupling is effective was not performed. The purpose of the present work is to examine the benefits of inter-pulse coupling in a well-controlled environment, evaluating the ignition probability and kernel growth rate as the PRF, total energy deposition, equivalence ratio, discharge gap distance, and flow velocity are varied. These results will be presented herein, along with high frame-rate imaging of the ignition events using the schlieren technique to visualize the ignition kernel development.

2. Experimental setup

The experimental system is focused around a small tunnel designed to produce well-defined in-flow conditions for ignition experiments. A schematic of the system is presented in Fig. 1. The tunnel consists of a constant area cross-section with dimensions of 3.81 cm by 3.81 cm. The flow is introduced at one end of the tunnel and passes through three screens separated by 1.27 cm with mesh sizes chosen for the gas velocity range to provide a uniform flow. There are two 1.6 mm diameter lanthanated tungsten electrodes located 5.18 cm downstream of the screens in a pin-to-pin geometry. The electrodes are sharpened to a 10° half angle cone, and can be moved independently with micrometers to change the gap distance. The electrodes are electrically isolated from the tunnel with Teflon sheaths and inserts.

Flow of fuel and air in the tunnel is controlled by calibrated mass flow controllers with measured uncertainties of ±2% of the flow setting. For the current set of experiments, compressed air was used along with chemical grade methane (99% purity) to produce a range of equivalence ratios. Bulk flow velocities tested in the tunnel were in the range of 2.5–10 m/s. These velocities produced bulk Reynolds numbers of 6000 to 24,000, and therefore the flow was deemed to be well within the turbulent regime. A small flow of inert gas is supplied at the exit of the tunnel to prevent flame holding. Static pressure in the tunnel was maintained at approximately 100 kPa (ambient room conditions) for all experiments.

Optical access is maintained on two opposite sides (UV grade fused silica), starting upstream of the electrodes, allowing for the discharge and subsequent kernel development and flame propagation process to be imaged. High-frame-rate schlieren was used to capture the global ignition process. This was accomplished with a continuous light source (Hg-Xe lamp), two spherical mirrors, a knife edge, and a Photron SA-Z camera. The system allowed for imaging at 40,000 frames per second (fps) of the density gradients produced by the discharge and combustion processes, allowing for tracking of the ignition kernel. The imaging resolution is 0.15 mm/pixel, which also defines the uncertainty in the gap distance.