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kHz-rate particle-image velocimetry of induced instability in premixed propane/air flame by millisecond pulsed current–voltage ☆

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ABSTRACT

Particle-image velocimetry (PIV) measurements were performed at 6 kHz repetition rate in a premixed propane/air flame to examine the effects caused by applied millisecond-wide pulsed voltage–current below self-sustained breakdown. We have demonstrated significant structural changes to a burner-stabilized downward-propagating atmospheric pressure propane/air flame with overall flow speeds near 2 m/s with +3 kV pulsed applied voltages over 30 mm gaps. Phase-locked, 2 kHz broadband emission measurements of flame structure were also collected to support the PIV velocity data. The combined high-speed PIV and flame emission measurements were both capable of capturing changes from a single applied voltage pulse rather than using a phase matching approach requiring a highly repeatable disturbance as done previously [1]. The measured reductions in flame height, increases in local flow speeds, generation of large velocity gradients, and rapid oscillations in flame front are suggestive of an induced turbulence in an otherwise laminar flame. Taylor microscale lengths were calculated from the kHz PIV data and structures comparable to the reaction zone thickness were shown to increase during the applied voltage pulse. The timescale under which the flame flow changes combined with the accompanying flame emission measurements suggest that flame fluidics are modified by ion drift current induced net body force in or near the cathode fall at the base of the flame. The reduction in overall flame height and increase in speed near the base of the flame is suggestive of a 'virtual' bluff-body present in the flow. These fluidic changes force the flame to transition from a laminar to a highly unstable, transitioning to turbulence regime.

1. Introduction

The interactions between flames and electric fields have been studied for well over a century [2,3]. Both premixed and non-premixed flames subjected to an electric field have been investigated and the main effects observed are changes in flame stability and emissions [4–12]. Through all of the research there exist two predominant possibilities for the observed effects; either an 'ionic wind' is responsible for modifying fluidics through ion-neutral collisions resulting from the directed flow of positively charged ions towards the cathode or the sub-breakdown electric field is capable of modifying chemistry before, during, and/or after combustion [4–12] This research is aimed at resolving the main cause of flame perturbation produced by a sub-breakdown positive polarity voltage induced chemi-ion current flow.

Early research with applied electric fields showed significant improvement in overall flame stability in both laminar and turbulent flames [4,5] and work by Wilson [6] is one of the first papers detailing the effects of ionic wind. A recent review by Fialkov [7] includes a detailed updated description of current work and provides a good description of ionic wind phenomena. Other research in these areas have expanded these results and shown better flame stabilization with an AC electric field [8] and as large as a 5× increase in blow off velocities for a methane/air, Bunsen-style flame [8,9]. Numerical work aimed at investigating the stabilizing mechanism and predicting flame behavior in flames subjected to electric fields has concluded that it is possible for an 'ionic wind' alone to be responsible for observed flame changes [10,11]. However, overall flame stabilization is not the only benefit observed and explored by researchers. An order of magnitude reduction in carbon monoxide emissions is reported by Sepp and Ulybyshev [12] and work by Sakhrieh et al. [13] has shown that reductions as high as 90% and 25% for CO and NO_x, respectively, were possible with a DC electric field applied to the flame. Saito [14] used a similar setup to Sakhreih and with a weaker electric field and recorded ~90% decrease in soot production. Others have found var-

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iation of flame structure, but minimal changes to NO_x emissions with results being highly dependent on anode/cathode configuration [15]. A number of these studies have shown that the effects observed in the flame are proportional to the magnitude of the electric field [9,10,14] and that parameters, such as laminar flame speed, scale with the imposed electric current or power [16]. If the current reaches sufficient levels, large scale changes can occur in premixed flames and can cause the overall flame structure to crush down [17,18]. There is a lack of direct experimental evidence and/or robust modeling presenting the exact mechanism by which the applied voltage, below self-sustained breakdown, modifies the flame fluidics and/or kinetics. Thermal [19], chemical [18,20], and fluidic effects [1,18] have been studied under the same flame condition to help elucidate direct effects from the induced effects on the flame. With thermal and chemistry changes neglected, the most popular argument is that the 'ionic wind' is predominantly responsible for the observed changes. A direct quantification of such effects can be obtained from measurements of the applied voltage–current-induced perturbation of the flow velocity and heat release rate. Particle-image velocimetry (PIV) and chemiluminescence imaging of the perturbed flame are very well suited to quantify the mechanisms which can cause a significant perturbation of the flame. Since the modification of fluidics itself can impact the flame kinetics, a time evolution of the measurements is required to isolate the cause and effects of chemi-ion current-induced flame perturbation. Previous measurements with a 10 Hz PIV system [1] have demonstrated high levels of initial repeatability in the flame behavior, but stochastic oscillations observed later in the applied voltage pulse vary greatly from pulse to pulse and prohibit accurate quantification of flame structure behavior from a single applied voltage pulse. These previous measurements have relied on phase-averaged temporal sequences to reconstruct temporal evolution of flame structure response and are unable to track incremental response to a single applied voltage pulse. To better understand the onset and the subsequent behavior of the flame subjected to a pulsed-applied voltage, we have measured space–time-resolved flame structure modification of a premixed C_3H_8/air flame that had been perturbed by 30 ms (milliseconds) wide pulsed applied voltage below self-sustained breakdown through the use of phase-locked kHz-PIV measurement. The resulting kHz-rate velocity vectors and related parameters, such as velocity gradients and turbulence lengths, are well suited to track fluidic changes to a laminar flame subjected to a single ms-scale applied voltage. Specifically, calculation of Taylor microscale lengths will help determine when intermediate turbulence length scales become sufficiently small values to impact flame behavior.

Proper Orthogonal Decomposition (POD) is a method for computing the optimal linear solution that represents a sample set of data and can separate a variable field into ordered energy. POD can be used on the kHz data from a single applied voltage pulse to help separate the fluctuating spatial features from the mean by looking at the spatial energy modes. These modes can vary in time and also provide the temporal history of each feature revealing which modes were most prevalent and when.

Since we are also interested in the flame structure modification, time-resolved volume-averaged broadband emission images are also collected at 1 kHz repetition rates. These images are used as a complementary visualization diagnostic for flame front structure to quantify the coupling between the flow velocity and flame kinetics perturbation. These data sets are used together to get a better fundamental understanding of the mechanism which initiates the observed flame speed increase process, paying special attention to the onset mechanisms. *The kHz repetition rates enable observation of both chemical kinetic and fluidic response of a premixed, hydrocarbon flame to a single applied voltage pulse.* Previous measurements of the effects of positive polarity pulsed electric fields relied on 'stitched' temporal sequences or averaged images that depend on the repeatability of the induced perturbation, consistency of seeding and flow conditions for high accuracy. Effort is taken to setup the electrical system to match that of previous studies [1,18–21].

2. Experimental setup

The experimental setup used to resolve and record the flow disturbance caused by a millisecond-timescale applied voltage, is shown in Fig. 1. This setup which closely resembles the setup used in previous work is discussed in detail elsewhere [1,19]. A 1-mm-diameter molybdenum wire is suspended 30 mm above the burner surface to serve as an anode for the application of positive voltage. The anode is placed directly above the flame tip, but not in the laser sheet to prevent unwanted surface scatter. The +3.0 kV pulsed voltage was applied using a 200 kΩ current-limiting ballast resistor, which is connected between the anode and the DC voltage power supply to limit current and prevent arcing. The voltage is pulsed at 10 Hz which allows the flame to fully recover to the 'no voltage' condition between each voltage pulse ensuring that every observed perturbation is created from that voltage pulse and not from an additive effect from previous applied voltage pulses. The voltage and corresponding current traces were recorded with an oscilloscope for each test condition and representa-

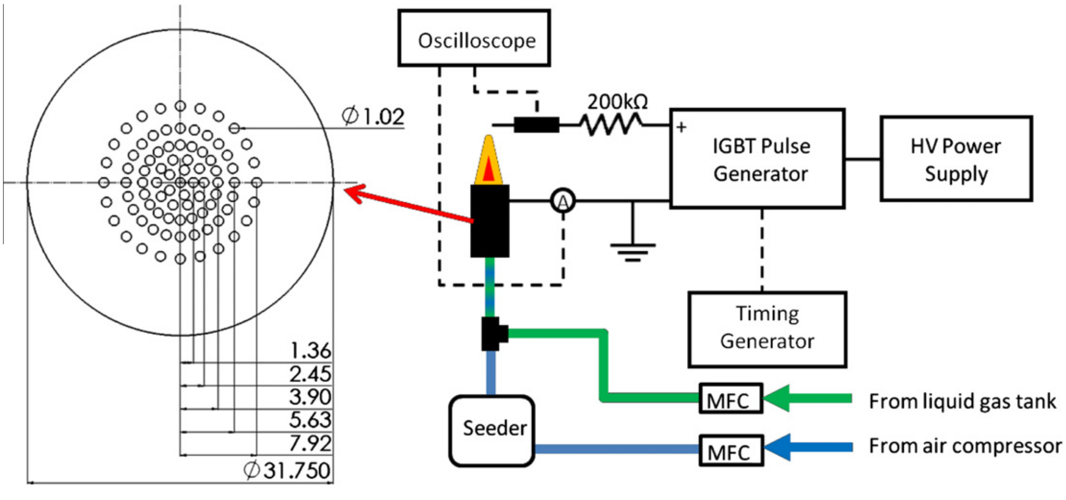

Fig. 1. Schematic of electrical and flow setup for applied voltage system. Burner geometry of concentric holes is shown on left. Burner dimensions are in millimeters.