Flame Oscillations Excited by a Ns Pulse / Ms Tail Electric Discharge Waveform

Yong Tang$^{1,2}$, Marien Simeni Simeni$^1$, Qiang Yao$^2$, Kraig Frederickson$^1$, and Igor V. Adamovich$^1$

$^1$ Nonequilibrium Thermodynamics Laboratory
Department of Mechanical and Aerospace Engineering
The Ohio State University, Columbus, OH 43210, USA

$^2$ Key Laboratory for Thermal Science and Power Engineering of Ministry of Education,
Department of Energy and Power Engineering, Tsinghua University, Beijing, 100084, China

Abstract

A repetitive ns pulse discharge voltage waveform is used to excite oscillations of a counterflow atmospheric pressure flame. A baseline ns pulse discharge operated at 10 Hz results in a relatively modest oscillatory response of the flame. Manipulating the external circuit to add a variable duration tail to the discharge pulse, without changing the pulse shape during breakdown or the pulse repetition rate, considerably enhances the impulse of the electrohydodynamic (EHD) force and increases the amplitude of the flame oscillations. To quantify this effect, the electric field during and after the discharge pulse is measured by ps Electric Field Induced Second Harmonic diagnostic. The electric field in the plasma is maintained during the voltage tail, although it is lower compared to the Laplacian field due to charge accumulation on the dielectric sleeves covering the electrodes. The time scale of the flame oscillations, ~10 ms, is limited by the relatively slow momentum transfer from the ions to the neutral species. The results demonstrate feasibility of enhancing the flame control authority, by combining the high electron / ion density generated by a ns pulse discharge with the EHD force applied on a much longer time scale.
1. Introduction

The effect of sub-breakdown AC and DC electric fields on flame stabilization has been studied extensively over the last several decades [1,2], as well as more recently [3-19]. Over the last decade, the scope of these studies has expanded to include the effect of electric discharges, primarily those sustained by repetitive ns duration pulses [20-33]. The effect of sub-breakdown electric fields on the flame reaction zone can be described in terms of the electrohydrodynamic (EHD) force ("ion wind") [34-38]. Depending on the flame and flow geometry, as well as the electric field amplitude and frequency, the ion wind may displace and distort the reaction zone, induce flame instabilities, and generate coherent flow structures.

In electric discharges sustained by higher than breakdown electric fields, the effect on the flame is complicated significantly by the generation of excited species and radicals in the plasma, resulting in plasma chemical reactions, as well as by Joule heating accelerating the rate coefficients of chemical reactions. These processes may significantly increase the burning velocity, the flame speed, the blow-off limit, and the flammability limits [20-33]. Compared to these effects, significant EHD interaction in transient, low duty cycle plasmas, such as generated by repetitive ns pulse discharges, appears unlikely, in spite of high electron / ion densities. However, the slowly varying residual electric field produced by the charge accumulation on dielectric surfaces, such as occurs in dielectric barrier discharges, may well increase the effective duty cycle and therefore the magnitude of the ion wind effect. In Ref. [22], the effect of a ns pulse electric discharge on the lifted jet flame was detected only when a dielectric barrier was used, indicating that the ion wind was the dominant factor in flame stabilization.

Quantifying the enhanced plasma / EHD effect on the flame requires measurements of the electric field distribution in the plasma, since the externally applied field may be perturbed significantly by the charge separation and charge accumulation on the dielectric surfaces. In the present work, we are using ps Electric Field Induced Second Harmonic (E-FISH) diagnostic [39-42]. The electric field is put on the absolute scale by measuring a Laplacian field during the voltage pulse ∼100 ns duration, before breakdown. The objectives of this work are to demonstrate that adding a long (ms time scale) tail to the ns pulse discharge waveform may enhance significantly the EHD effect on the flame, and to quantify the flame forcing by measuring the electric field distribution during the discharge pulse and in the afterglow, in simple geometry. These proof-of-concept experiments may result in the development of an effective combustion stabilization / flameholding method.

2. Experimental

Figure 1 shows a schematic of the burner, the flame, the discharge electrode assembly, and the position of the laser beam. A custom-made burner is used to sustain a laminar counterflow diffusion flame in a mixture of 14% CH₄ / 84% Ar (bottom) and 42% O₂ / 58% Ar (top), with the nitrogen co-flow. The diameters of the inner and co-flow nozzles are D₁=10 mm and D₂=16 mm respectively, and the gap between the fuel and oxidizer nozzle exits is Δ₁=15 mm. The flow rates
of the fuel and oxidizer mixtures are 1.25 and 1.25 slm, and the co-flow rates are 2.25 slm (top) and 0.75 slm (bottom).

The discharge is generated between two parallel brass rod electrodes $d_1=1.5$ mm in diameter, covered by alumina ceramic tubes with the outside diameter of $d_2=3$ mm, as shown in Fig. 1. The overlap between the electrodes is $L_0=24$ mm, with the non-overlapping length for each electrode is $L_1=6$ mm, and the electrode gap is $A_2=12$ mm. The electrodes are powered by a high-voltage pulse generator producing alternating polarity pulses with peak voltage of up to $U_{peak}=16$ kV and pulse repetition rate of 20 Hz. The alternating polarity pulse train is converted to a positive-polarity, 10 Hz pulse train by using ultra-fast high-voltage diodes connected in series between the high-voltage terminal of the pulse generator and the actuator electrodes, as shown in Fig. 1. Additional diodes placed between the high-voltage electrode and the 10 kΩ buffer resistor (see Fig. 1), are used to add a gradually decaying tail to the voltage pulse shape, several ms long, used to enhance the electric field effect on the flame. Figure 2 compares the pulse voltage waveforms measured with different number of diodes between the high-voltage electrode and the buffer resistor (n=0-6). Adding the extra diodes has essentially no effect on the pulse shape during the voltage rise and reduction, as long as the discharge current after breakdown remains significant. Basically, adding the diodes increases the effective buffer resistance during the voltage reduction by several orders of magnitudes, compared to the baseline case, and increases the voltage fall time from a few hundred nanosecond to several milliseconds.

The schematic of ps E-FISH laser diagnostics is essentially the same as in our previous work [41,42]. Briefly, the fundamental, vertically polarized output beam of an Ekspla PL2143A Nd:YAG laser, with a pulse duration of 30 ps and pulse energy of 10 mJ, operating at 10 Hz, is focused into the discharge / flame region, using a 100 cm focal distance lens. The signal beam is recollimated and focused onto the entrance slit of a monochromator, followed by a narrowband pass filter, and detected by a photomultiplier tube. The signal is proportional to the square of the electric field, averaged nearly uniformly over the span of the overlapping electrodes [42] (see Fig. 1). Absolute calibration of the measurements is obtained from the known electrostatic electric field generated halfway between the electrodes during the ns pulse voltage rise, before breakdown. The electrostatic electric field distribution is calculated by solving the Laplace equation for the electric potential, for the given electrode geometry.

3. Results and Discussion

Figure 3 shows a collage of single-shot, 10-ns camera gate plasma emission images taken during the discharge pulse, as well as the long gate images (400 ns showing the entire discharge pulse, and 100 µs showing the flame). These images are taken in a positive polarity “baseline” discharge sustained across the flame plane, without the extra diodes between the high voltage electrode and the buffer resistor (i.e. at n=0). Both the axial view (along the electrodes) and the side view are shown. It can be seen that the discharge generates a relatively diffuse plasma in the plane of the electrodes and across the flame, although the filamentary structure on the bottom (fuel) side is apparent.
Figure 4 shows the time-dependent Laplacian field, calculated by multiplying the normalized solution of the Laplace equation by the applied voltage waveform, and the time-resolved vertical component of the electric field in the baseline ns pulse discharge (n=0) sustained at 10 Hz in the counterflow flame, plotted at three different locations between the electrodes. It can be seen that the use of the Laplacian field during the voltage rise, before breakdown, for calibration is justified since the electric field offset before the discharge pulse is typically small, with the exception of the measurements near the grounded electrode, where it introduces an estimated 10% uncertainty in the calibration. After breakdown, the electric field at all three locations is reduced significantly due to the plasma self-shielding, as also observed in our previous measurements of electric field in ns pulse discharges in air and hydrogen, as well as in a hydrogen diffusion flame [41,42]. The data taken before and during the voltage rise (specifically, the field behavior at z=1 mm, -200 ns < t < -50 ns, see Fig. 4) indicate the electric field reversal between the discharge pulses, such as has been detected in our previous measurements in a surface plasma flow actuator [41]. The field reversal is caused by the charge accumulation on the dielectric surfaces covering the electrodes, which may persist for a long time after the applied electric field is removed [41]. At the present conditions, this effect is relatively weak, except near the grounded electrode.

Figure 5 shows the results of the electric field measurements in a ns pulse discharge with n=4, operated at 10 Hz, with a long tail (2 ms FWHM) at the trailing edge of the voltage pulse waveform (see Fig. 2). At these conditions, the deviation of the measured field from the Laplacian field is less pronounced, which suggests that the electron density in the plasma may be lower compared to the baseline discharge. This effect may be due to the suppression of the filaments detected in the baseline discharge plasma, when the extra diodes are added to the external circuit to produce the long tail in the voltage waveform. It can also be seen that adding the tail generates a fairly significant electric field after the discharge pulse, in the range of 2-5 kV/cm at the measurement locations, on the time scale of several hundred ns.

Figure 6 shows a collage of flame emission images, illustrating flame oscillations excited by a baseline ns pulse discharge operated at 10 Hz, taken during the 100 ms interval between the discharge pulses. It can be seen that the discharge induces the flame distortion and oscillations, with the amplitude of approximately 1-2 mm, on the time scale much longer compared to the discharge pulse duration (~ 10 ms vs. ~100 ns). As discussed in Ref. [33], this may be due to the increase in the burning velocity in the plasma, which results in the flame front perturbation. However, the long time scale on which this effect is observed suggests that the effect may be rather due to the weak residual electric field between the discharge pulses, near detection limit of the present diagnostic, producing an EHD force on the charged species generated during the discharge.

Figure 7 compares two sets of flame emission images in a ns pulse discharge operated at 10 Hz, with long tail added to the voltage waveform, taken at the same moments of time. The results in Fig. 7 are shown for different number of extra diodes between the high-voltage electrode and the buffer resistor, n=2 and n=6. It is readily apparent that the amplitude of the flame oscillations for n=2 and n=6 is significantly higher compared with that for the baseline case of n=0. The oscillation amplitudes at n=4 and n=6 are close, suggesting that the effect is near saturation, such that further increase of the tail length would not result in an additional increase of the
amplitude. Note that adding the extra diodes and extending the voltage waveform tail does not change the pulse energy coupled to the plasma (the estimated upper bound difference in the energy coupled with and without the tail is several tens of μJ/pulse, much smaller compared to the baseline coupled energy of 0.5 mJ/pulse). Therefore at these conditions the effect on the flame is almost certainly due to the electrohydrodynamic interaction (“ion wind”). Basically, no additional ionization is generated during the voltage waveform tail, and the enhanced effect of the flame is produced by the transport of the ions generated during the discharge pulse by the electric field on a much longer time scale, increasing the impulse of the EHD force.

4. Summary

In the present work, oscillations of an atmospheric pressure, counterflow CH\(_4\)-O\(_2\)-Ar flame are induced by repetitive, ns duration, high voltage pulses combined with a gradually decaying, ms duration tail. The electric field during the ns pulses, which generates a plasma between the electrodes, and in the afterglow between the pulses, is measured by ps E-FISH diagnostic. Absolute calibration is obtained from the second harmonic signal measured during the voltage rise, before breakdown, when the electric field between the electrodes remains Laplacian. The results show that ns discharge pulses without the tail produce low-amplitude flame oscillations when operated at a repetition rate of 10 Hz. Although the electric field between the discharge pulses at these conditions is low, near the detection limit, the long time scale of the flame oscillations, ~ 10 ms, suggests that they are induced mainly by the residual EHD force on the charged species generated in the discharge. Adding a variable, ms duration, tail to the ns pulse voltage waveform increases the flame oscillation amplitude considerably, as the tail duration is increased. Since the discharge pulse waveform, during the period when the conduction current is detected, remains essentially the same, this effect is almost certainly caused by the electric field in the tail, producing the EHD force (“ion wind”) on the charges generated during the discharge pulse. Basically, adding the tail greatly increases the impulse of the EHD force, without generating additional charges or increasing the energy input in the plasma. The electrode geometry can be optimized to enhance the residual electric field component in the desired direction. Based on the experimental results demonstrating the effect of dielectric barrier ns pulse discharges, as well as sub-breakdown DC and AC fields, on stability of a lifted jet flame [22] and on the present data, combining a ns pulse discharge voltage waveform with a long tail enhancing the EHD effect may be used for efficient flameholding in high-speed, high-pressure flows.

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Figure 1. Schematic of the experimental setup (a,b). Photos of the burner with the electrodes in place and the flame, (c) axial view and (d) side view.
Figure 2. Pulse voltage and current waveforms measured with different number of diodes between the high-voltage electrode and the ballast resistor (n=0-6).

Figure 3. Single-shot, 10-ns camera gate plasma emission images taken during the discharge pulse and long gate images (400 ns showing the entire discharge pulse, and 100 μs showing the flame) in a positive polarity “baseline” discharge (n=0), axial view (top) and side view (bottom). The locations of the electrodes are indicated with dashed lines.
Figure 4. Time-dependent Laplacian field (curves) and measured time-resolved electric field (symbols) in the baseline ns pulse discharge (n=0).

Figure 5. Time-dependent Laplacian field (curves) and measured time-resolved electric field (symbols) in a ns pulse discharge with a long tail added to the voltage waveform (n=4).
Figure 6. Collage of flame emission images illustrating flame oscillations excited by a baseline, positive polarity, ns pulse discharge operated at 10 Hz. Camera gate 1 ms.

Figure 7. Collage of flame emission images comparing flame oscillations excited by a ns pulse discharge operated at 10 Hz, with long tail added to the voltage waveform: n=2 (a) and n=6 (b).