Counterflow Diffusion Flame Oscillations
Induced by Ns Pulse Electric Discharge Waveforms

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Abstract

Repetitive ns pulse, dielectric barrier discharge voltage waveforms, combined with a tail
several ms long, are used to induce oscillations of a counterflow atmospheric pressure diffusion
flame. A baseline ns pulse discharge operated at 10 Hz results in a relatively modest oscillatory
response of the flame, which becomes more pronounced in burst mode operation, at the same burst
repetition rate of 10 Hz. This effect is most likely caused by the residual electric field after the
discharge pulse, producing the electrohydrodynamic (EHD) force (“ion wind”) on the charges
generated during the discharge, although plasma chemistry and Joule heating by the discharge may
also contribute. 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 EHD force and increases the amplitude of the flame
oscillations. To quantify this effect, the electric field distribution between the electrodes during
and after the discharge pulse is measured by ps Electric Field Induced Second Harmonic (E-FISH)
diagnostic. The results show that the electric field is maintained during the voltage tail, although
it is lower compared to the Laplacian field due to the charge accumulation on the dielectric sleeves
covering the electrodes. The time scale of the flame oscillations at the present conditions, of the
order of ~10 ms, is limited by the relatively slow momentum transfer from the ions to the neutral
species. The present results demonstrate feasibility of enhancing the flame control authority, by
combining a high peak ionization fraction generated by a ns pulse discharge with the EHD force
applied on a long time scale, using a single plasma generator.
1. Introduction

The effect of sub-breakdown AC and DC electric fields on flame stabilization has been studied extensively over the last several decades (e.g. [1,2] and references therein), 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], since they generate more stable and reproducible high-pressure plasmas compared to most DC, AC, RF, and microwave discharges. Generally speaking, 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], although its accurate quantitative description requires the development and validation of a high fidelity kinetic model incorporating detailed kinetics and transport of positive and negative ions, as well as electrons. 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 [4,5,8,12,13,18,19], induce flame instabilities [3,6,9,11], and generate coherent flow structures [10,14-17]. Qualitatively, the magnitude of this effect is limited by the EHD interaction parameter (the ratio of the Coulomb force work to the flow kinetic energy) [39]

\[
\eta \sim \frac{\varepsilon_0 E^2}{\rho u^2} \xi \sim \frac{e n_i \Delta \phi \xi}{\rho u^2}, \tag{1}
\]

where \(\varepsilon_0\) is dielectric permeability of vacuum, \(n_i\) is the ion number density, \(E\) and \(\Delta \phi\) are the electric field and the potential difference across the space charge region (e.g. the reaction zone), \(\xi\) is the applied electric field duty cycle, \(\rho\) and \(u\) are the flow density and velocity. For the EHD force interaction to be significant, the interaction parameter should be of the order of one, \(\eta \sim 1\). Since chemi-ionization processes in flames generate fairly low ion density, \(n_i \sim 10^8-10^{11} \text{ cm}^{-3}\) [2], this limits the applicability of EHD interactions to relatively low-speed flows.

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 the Joule heating accelerating the rate coefficients of chemical reactions. As discussed in numerous experimental studies, 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 highly transient, very low duty cycle plasmas (\(\xi \sim 10^{-5} - 10^{-3}\)), such as generated by repetitive ns pulse discharges used in most plasma assisted combustion studies, appears unlikely, in spite of much higher electron / ion densities, up to at least \(n_i \sim 10^{14}-10^{15} \text{ cm}^{-3}\) [40]. However, the slowly varying residual electric field produced by the charge accumulation on dielectric surfaces, such as occurs in dielectric barrier discharges [41], 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. In this study, the effect of a dielectric barrier ns pulse discharge on the flame lift-off height was also found to be comparable to that of sub-breakdown DC field and AC fields.

The magnitude of the EHD interaction may be increased significantly by combining the pulsed discharge, which generates a much higher electron / ion density compared to chemi-ionization in a flame, with a sub-breakdown DC or AC electric field, with a much higher duty cycle. Therefore this approach may produce a greater time-integrated impulse of the EHD force,
limited by the peak electron density generated during the discharge pulse, the rate of electron-ion and ion-ion recombination, and the breakdown threshold between the discharge pulses.

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 [42,43], which has also been employed in our previous experiments in ns pulse discharge plasmas sustained in air and in a hydrogen diffusion flame [44,45]. At the present conditions, 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. For this, we monitor the amplitude of the oscillations of the reaction zone of a non-premixed counterflow flame, which is known to be sensitive to the electrohydrodynamic forcing [14-16]. These proof-of-concept measurements may contribute to the development of an effective combustion stabilization / flameholding method, as well to the development and validation of a predictive kinetic modeling of the electric-discharge enhanced EHD forcing of the flame. Such a model needs to incorporate electron impact ionization processes and plasma chemical reactions, Joule heating, electron / ion transport, and their coupling to the neutral flow, in a realistic geometry.

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 / 86% Ar (bottom) and 42% O2 / 58% Ar (top), with the nitrogen co-flow. The diameters of the inner and co-flow nozzles are \( D_1 = 10 \text{ mm} \) and \( D_2 = 16 \text{ mm} \), respectively, and the gap between the fuel and oxidizer nozzle exits is \( \Delta_1 = 15 \text{ mm} \). The flow rates of the fuel and oxidizer mixtures are 1.25 slm each, and the co-flow rates are 2.25 slm (top) and 0.75 slm (bottom). The fuel and oxidizer mixture compositions are set up to match the momenta of the two flows, based on the volume flow rates and molecular weights of the components. The \( N_2 \) co-flow rates are chosen to help balance the effect of buoyancy and to reduce the flame distortion when the electrodes are put in place. The estimated flow velocity at the exit of the fuel and oxidizer nozzles is \( U_0 = 26 \text{ cm/s} \), and the estimated co-flow velocity is \( U_{1t} = 30 \text{ cm/s} \) (top) and \( U_{1b} = 10 \text{ cm/s} \) (bottom). The momenta of the fuel and oxidizer flows are balanced. The Reynolds number based on the nozzle exit diameter is \( Re_{D1} \approx 130 \). The flame diameter is approximately 25 mm. As expected, the flame is not entirely flat, with the peripheral part slightly lifted by the buoyancy of the combustion products. Temperature distributions in the flame with and without the effect of buoyancy, predicted by 2-D axisymmetric simulations of a non-premixed counterflow laminar flame using OpenFOAM software with GRI-Mech 1.2 combustion mechanism [46] demonstrate that incorporating buoyancy results in the lifting of the outer edge of the flame, consistent with the experimental observations.

The discharge is generated between two parallel brass rod electrodes \( d_1 = 0.6 \text{ mm} \) in diameter, covered by alumina ceramic tubes with the outside diameter of \( d_2 = 1.5 \text{ mm} \), as shown in
Fig. 1. The overlap between the electrodes is $L_0=24$ mm, with the non-overlapping length for each electrode of $L_1=6$ mm, and the electrode gap of $\Delta =12$ mm. The laser beam is directed parallel to the electrodes. The burner / electrode assembly is mounted on a three-dimensional translation stage, such that the laser beam can be moved relative to the flame and the electrodes, in the plane of the electrodes. Putting the electrodes in place somewhat distorts the flame and displaces it approximately 1-2 mm above the horizontal plane of symmetry (see Fig. 1). In the present work, two parallel insulated rod electrodes are used, rather than two parallel mesh electrodes, to prevent the discharge filamentation and to generate a more diffuse plasma.

The electrodes are powered by a custom-made high-voltage pulse generator producing alternating polarity pulses with peak voltage of up to $U_{\text{peak}} =16$ kV and pulse repetition rate of 20 Hz. The alternating polarity pulse train is converted to a positive-polarity, 10 Hz pulse train, essentially without the pulse waveform distortion, by using ultra-fast high-voltage diodes (UF1007-T) connected in series between the high-voltage terminal of the pulse generator and the actuator electrodes, as shown in Fig. 1. Additional diodes are placed between the high-voltage electrode and the 10 kΩ buffer resistor (see Fig. 1), to slow down the voltage reduction on the electrode by several orders of magnitude. This results in adding a gradually decaying tail to the voltage pulse shape, several ms long, used to enhance the electric field effect on the flame. The discharge voltage and current waveforms are measured by the Tektronix P-6015 high voltage probe (bandwidth 75 MHz) and Pearson 2877 current probe (bandwidth 200 MHz). Plasma emission images are taken by the Princeton Instruments PI-Max 3 ICCD camera with a UV lens. Figure 2 plots the baseline discharge pulse voltage and current waveforms measured without the additional diodes between the high-voltage electrode and the buffer resistor, plotted together with the capacitive current, calculated using the measured stray capacitance of the electrodes, $C_{\text{stray}} = 0.44$ pF. The flame has a negligible effect on the stray capacitance. It can be seen that the discharge current exceeds the capacitive current by almost an order of magnitude. The labels “breakdown”, “peak”, and “current decay” indicate the moments when the electric field distributions along the discharge gap were measured (see the discussion of Fig. 9 below).

Figure 3 compares the pulse voltage waveforms measured with different number of diodes between the high-voltage electrode and the buffer resistor (n=0-6). As expected, adding the extra diodes has essentially no effect on the pulse shape during the voltage rise and even during the voltage reduction, as long as the discharge current after breakdown remains significant. Basically, the voltage pulse shape changes only during the voltage reduction, after the conductivity of the discharge gap is reduced significantly below the peak value during the discharge pulse. At these conditions, the effective buffer resistance becomes extremely high (estimated to be $R_b \sim 1$ GOhm), resulting in a very long voltage decay time, $\tau_{\text{decay}} \sim R_b C_{\text{stray}} \sim 1$ ms. Thus, adding the diodes increases the effective buffer resistance after the conduction current decay 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, shown in Fig. 4, is essentially the same as in our previous work [44,45]. 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 laser beam diameter at the focal point, measured by traversing a razor blade across the beam, is approximately 200 μm, with the Rayleigh range of about $z_R \approx 3$ cm. The focal point of the beam is placed at the center of the discharge electrode assembly. The second harmonic signal beam is
separated from the fundamental beam using a pair of dichroic mirrors and a dispersion prism, as shown in Fig. 4. The signal beam is collimated and focused onto the entrance slit of a monochromator, followed by a narrowband pass filter (50% transmission at 532 nm, 10 nm band pass), and detected by a photomultiplier tube (PMT). A polarizer mounted on a rotation stage before the focusing lens isolates the second harmonic signals generated by the vertical and horizontal electric field components, since the signal polarization is parallel to the direction of the field. At the present conditions, the root mean square value of the electric field, averaged nearly uniformly over the span of the overlapping electrodes [45] (see Fig. 1), is measured. The timing and the pulse energy of the fundamental laser beam are monitored by a photodiode.

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. During the calibration and measurements in the discharge, the PMT voltage is kept sufficiently low to avoid its saturation at high electric fields [44].

3. Results and Discussion

Figure 5 shows a set 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). In Fig. 5 and all subsequent figures, t=0 represents the moment when the applied voltage peaks, as indicated in Fig. 2, and the time stamps indicate the moments when the camera gate opens. These images are taken in the 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. The locations of the electrodes in the images are indicated with dashed lines. 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 readily apparent. Figure 6 shows a set of images taken in a positive polarity discharge with four diodes between the high voltage electrode and the buffer resistor (n=4). Comparison of the two sets of plasma images (n=0 and n=4) shows that the plasma produced in a ns pulse discharge with a tail several ms long appears more diffuse, with no sign of well-defined individual filaments detected in the baseline ns pulse discharge. This is confirmed by further comparison of the emission images taken with a long camera gate, 400 ns (showing the plasma emission integrated over the entire discharge pulse), and 100 μs (also showing the flame), for n=0-6, illustrated in Fig. 7. Since adding the extra diodes does not change the voltage waveform during the discharge pulse, this behavior is not completely understood, but it is likely that the electron and ion transport by the electric field in the pulse tail, on a ms time scale, helps reduce the nonuniformity of the residual electron density distribution between the pulses, precluding the filament formation by the subsequent voltage pulse.

Figure 8(a) plots the calculated Laplacian field distribution between two parallel rod electrodes in alumina ceramic sleeves for the applied voltage of 14.5 kV, which was used for the absolute calibration of the measurements. For a lower peak voltage of 8 kV, when no plasma is generated in the gap, the measured electric field follows the Laplacian electric field during the entire voltage pulse, as illustrated in Fig. 8(b). Figure 9(a) 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, indicated schematically in the inset. It can be seen that the use of the Laplacian field for calibration during the voltage rise, before breakdown, 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 observed in our previous measurements of electric field in ns pulse discharges in air and hydrogen, as well as in a hydrogen diffusion flame [44,45]. The data taken before and during the voltage rise (specifically, the field behavior at z=1 mm, -200 ns < t < -50 ns, see Fig. 9(a)) indicate the electric field reversal between the discharge pulses, such as has been detected in our previous measurements in a surface plasma flow actuator [44]. 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 [44]. At the present conditions, this effect is relatively weak, except near the grounded electrode.

Figure 9(b) shows the vertical component of the electric field measured at different locations across the discharge gap near the breakdown moment at z=0 (at t=-20 ns), as well as at peak voltage (at t=0 ns) and after the discharge current decay (at t=20 ns, see Fig. 2), at the conditions of Fig. 9(a). The spatial distribution of the vertical component of the Laplacian field for the peak applied voltage of U_{peak} = 14.5 kV used in these measurements is shown for comparison. As expected, the electric field near the grounded electrode remains significantly higher compared to that in the middle of the gap, although at all locations across the discharge gap, the electric field after breakdown is significantly lower compared to the “nominal” Laplacian field corresponding to the applied voltage at that moment of time.

Comparison of the temporal variation of the electric field at different spatial locations, shown in Fig. 9(a), and the spatial variation of the field at different moments of time, plotted in Fig. 9(b), indicates that the electric field varies rapidly in time during and after the discharge pulse, on the time scale of tens to hundreds of ns. On the other hand, the electric field distribution in the gap during the discharge pulse remains smooth and does not exhibit well-defined isolated maxima indicative of ionization waves propagating in the discharge gap, such as detected in our previous work [47].

Figure 10 plots the time-dependent Laplacian field and the time-resolved electric field measured in the baseline ns pulse discharge operated in burst mode, at the pulse repetition rate of 250 Hz, burst repetition rate of 10 Hz, and with 10 pulses in a burst (burst duration 40 ms). The data shown in the figure are measured during the pulse #6, i.e. at t=20 ms. Although these data are qualitatively similar to the results obtained in the baseline discharge operated at 10 Hz, it is readily apparent that the deviation of the electric field after breakdown from the Laplacian field is less pronounced. This appears somewhat counterintuitive, both since the pulse repetition rate during the burst remains low (such that the residual ionization from the previous pulse is likely to be insignificant), and since higher residual ionization would only increase the effect of plasma self-shielding [48]. This nature of this effect is understood better when the flame oscillations induced by the discharge are taken into account, as discussed below.

Figure 11 shows the results of the electric field measurements in a 10 Hz ns pulse discharge with n=4, with a long tail (2 ms FWHM) at the trailing edge of the voltage pulse waveform (see
Fig. 3). At these conditions, the deviation of the measured field from the Laplacian field is even less pronounced, which suggests that the electron density in the plasma may be lower compared to the baseline 10 Hz pulse discharge. This effect may be due to 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, as illustrated in Fig. 7. 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 12 compares the time-dependent Laplacian field with the absolute value of the electric field measured in the gradually decaying tail of the applied voltage pulse measured at different locations in the discharge gap at the conditions of Fig. 11 (n=4), on a longer time scale, up to 1 ms. Although the electric field in the gap is significantly lower compared to the Laplacian field, it is still detectable up to at least 1 ms, and is consistently higher compared to the field after the baseline ns pulse discharge without the tail. Also, the field near the grounded electrode, ≈ 1 kV/cm, is detected during the entire time period between the discharge pulses, 0.1-100 ms. Note that since the field reversal moment is difficult to identify from the relatively sparse data between the pulses, only the absolute value of the electric field is plotted in Fig. 12. To determine whether the electric field of this magnitude may produce an effect on the flame, sub-breakdown DC voltage in the range of 0.5-3.0 kV/cm was applied to the electrodes, resulting in a detectable displacement of the flame above ~1 kV/cm. The data in Figs. 9-12 illustrate and quantify the difference between the electric field in the gap after the discharge pulse, measured with and without the tail in the voltage waveform. The detection limit of the present diagnostics is approximately 0.5 kV/cm, limited by the stray second harmonic signal generated in the components of the optical system, which was subtracted from the signal generated in the plasma. As expected, the highest electric field is measured at z=5 mm, near the grounded electrode. At this location, the electric field above the sensitivity limit, approximately 1-3 kV/cm, is detected during the entire interval between the discharge pulses, up to t=100 ms (e.g. see Figs. 11,12), when the applied voltage is very low, indicating the effect of residual surface charge accumulation on the ceramic sleeve covering the grounded electrode.

Figure 13 shows a set of flame emission images, illustrating flame oscillations excited by the baseline ns pulse discharge operated at 10 Hz (at the conditions of Fig. 9), 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 shown in Fig. 14, operating the discharge in 10 Hz burst mode, at 250 Hz pulse repetition rate and 10 pulses per burst (burst duration rate of 40 ms), i.e. at the conditions of Fig. 10, enhances the effect on the flame considerably. In this case, it is apparent that the flame becomes strongly distorted near location of the plasma during the discharge burst (at t=0-40 ms), with the central part moving toward the grounded electrode. As discussed in Refs. [15,38], the body force induced by the applied electric field, enhanced by the ionization generated during the discharge at the present conditions, affects the bi-directional transport (diffusion and convection) of the fuel and oxidizer species in the discharge gap, resulting in the displacement of the counterflow diffusion flame. Since the electric field and electron density distributions between the parallel rod electrodes is not uniform, the central part of the flame, overlapping with the plasma, is moving toward the grounded electrode during the discharge burst (at t=0-40 ms), such that the flame becomes distorted.
After the discharge burst, the central part of the flame returns to near original position (at 60 ms), while the peripheral region of the flame moves out of phase with the central part (at 70-80 ms), resulting in a “flapping” motion (see Fig. 14). The flame displacement from the stationary position (without the discharge) is likely responsible for a somewhat weaker apparent effect of the discharge on the electric field after breakdown for burst mode operation, at t=20 ms, compared to the 10 Hz discharge (compare Figs. 9(a) and 10). In this case, the electric field during the discharge pulses in the middle of the burst (such as pulse #6 in Fig. 10) is measured in a lower temperature fuel (CH$_4$-Ar) mixture, rather than in the higher temperature reaction zone, such that the breakdown voltage is higher and the electron density is likely to be lower.

Finally, Figure 15 compares several sets of flame emission images in a ns pulse discharge operated at 10 Hz, with and without long tail added to the voltage waveform, taken at the same moments of time. The results in Fig. 15 are shown for different number of extra diodes between the high-voltage electrode and the buffer resistor, n=0 (baseline case, conditions of Fig. 9), n=2, n=4 (conditions of Fig. 11), and n=6. It is readily apparent that the amplitude of the flame oscillations for n=4 and n=6 is significantly higher compared with that at n=0 and n=2, demonstrating a strong effect of the residual electric field during the voltage pulse tail. The oscillation amplitudes at n=4 and n=6 are close, indicating that the effect is near saturation, such that further increase of the tail length would not result in an additional increase of the amplitude.

In the present work, the frequency of the flapping motion is the same as the forcing frequency (discharge pulse repetition rate or burst repetition rate of 10 Hz in Figs. 13-15), at all operating conditions. This is readily apparent both from the videos of the flame response to the forcing by the discharge, and from ICCD images such as shown in Fig. 13-15. Specifically, the flame images taken at a fixed time delay after the discharge pulse have excellent reproducibility, which illustrates that the flame oscillation frequency is the same as the forcing frequency. This fact is confirmed by the dynamic response of the flame between the discharge pulses (pulse bursts), illustrated in Figs. 13-15.

Increasing the discharge pulse repetition rate from 10 Hz to 20 Hz, when the forcing frequency becomes comparable with the global stretch rate of the flame, estimated as the ratio of the flow velocity and the nozzle gap, $a = U_0 / \Delta_1 = 17.7 \text{ m/s}$, reduces the oscillation 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 $\mu$J/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 longer time scale, thus 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 generate a plasma between the electrodes, and in the afterglow between the pulses, is measured by ps Electric Field Induced
Second Harmonic (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. The amplitude of the oscillations increases when the discharge is operated in burst mode, with 10 pulses per burst and the same burst 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, rather than by the chemical reactions of radical species generated in the plasma or the Joule heat produced during 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 producing additional charges or increasing the energy input in the plasma. This is consistent with the electric field measurements after the discharge pulse, showing that the electric field in the plasma persists during the voltage tail, although it remains lower compared to the Laplacian field, due to the accumulation of charges on the dielectric sleeves covering the electrodes. The characteristic time scale of the flame oscillations is of the order of ~10 ms, controlled by the relatively slow momentum transfer from the ions in the decaying plasma to the neutral species. It may be reduced by increasing the pulse peak voltage while reducing the pulse duration, which would increase the peak electron density in the plasma without inducing the discharge instability [49], and by operating the ns pulse discharge in burst mode. At the present conditions, generating higher frequency oscillations is also limited by the low flame stretch rate. However, this factor is expected to be less restrictive at a higher flow velocity through the reaction zone.

The sensitivity of the experimental observations (in particular the enhancement of the flame oscillations amplitude vs. the voltage pulse duration) to the equivalence ratio remains an open question, since it may strongly depend on the peak electron density and the rate of electron recombination at the location of the flame, and will be the subject of the future study. 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], as well as 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 counterflow burner, double dielectric barrier discharge electrode assembly, electric circuit, and the laser beam (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 without additional diodes between the high-voltage electrode and the buffer resistor, plotted together with the capacitive current. “Breakdown”, “peak”, and “current decay” indicate the moments when the electric field distributions along the discharge gap were measured (see Fig. 9(b)).
Figure 3. Pulse voltage and current waveforms measured with different number of diodes between the high-voltage electrode and the ballast resistor (n=0-6). Adding the diodes increases the effective buffer resistance by several orders of magnitudes, compared to the baseline case, and increases the voltage fall time.
Figure 4. Schematic of picosecond Electric Field Induced Second Harmonic (E-FISH) diagnostic.
Figure 5. 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 the positive polarity “baseline” discharge (n=0) sustained across the flame plane, axial view (left) and side view (right). The locations of the electrodes are indicated with dashed lines.
Figure 6. Single-shot, 10-ns gate plasma emission images, and long gate images (400 ns showing the entire discharge pulse, and 100 μs showing the flame) in a positive polarity discharge with n=4.
Figure 7. 400 ns gate plasma emission images, showing the entire discharge pulse, and 100 μs gate images showing the flame, in positive polarity discharges with n=0-6.
Figure 8. (a) Calculated Laplacian field distribution between two parallel rod electrodes in dielectric sleeves for the applied voltage of 14.5 kV, used for absolute calibration; (b) Time-dependent Laplacian field (curve) and measured time-resolved electric field (symbols) halfway between the electrodes for a lower peak applied voltage of 8 kV.
Figure 9. (a) Time-dependent Laplacian field (curves) and measured time-resolved electric field (symbols) in the baseline ns pulse discharge sustained at 10 Hz in the counterflow flame, at three different locations between the electrodes indicated in the inset; (b) Vertical electric field measured at different locations along the discharge gap near breakdown at $z=0$ ($t=-20$ ns), at peak voltage ($t=0$ ns), and after discharge current decay ($t=20$ ns, see Fig. 2). Spatial distribution of the vertical component of the Laplacian field for peak applied voltage of $U_{\text{peak}} = 14.5$ kV is shown for comparison. A schematic of the discharge pulse train is also shown.
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