# **Combustion Enhancement Using Silent Electrical Discharges**

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Abstract— Silent electrical discharges, also known as dielectric-barrier discharges (DBDs), can create free radicals and fragmented compounds that play a role in combustion reactions. Using silent discharge devices, we have carried out tests on hydrocarbon fuel activation systems capable of increasing flame speed, stabilizing flames, and operating in very lean burn regimes (where the production of pollutants such as  $NO_x$  and CO are expected to decrease). Experiments have been carried out with the gaseous hydrocarbon fuels methane, ethane, propane and butane, as well as the gasoline surrogate liquid iso-octane. In our experiments, the fuel alone is activated, before it is mixed with air and combusted.

Keywords— Plasma-assisted combustion, silent discharge, dielectric-barrier discharge.

# I. INTRODUCTION

The application of electric fields to flames has been studied at least as far back as 1814 [1], was applied to combustion in the 1920's [2], and was further developed into several applications in the last half of the 20<sup>th</sup> Century [3]. When the electric field strength is sufficient to cause electrical breakdown of a fuel or fuel/air mixture, plasma effects will dominate. Plasma effects can increase electron and ion temperatures and promote combustion through the formation of 'active' species (such as free radicals) or the dissociation of fuel molecules into smaller, more-easily combustible fragments.

Interest in applying non-thermal plasmas (NTPs) to altering hydrocarbon combustion is growing [4, 5]. In studies reported in the literature, electric-discharge driven NTPs have been directly applied to a flame region or to a fuel/air, pre-flame mixtures [6-8]. We have chosen the dielectric barrier discharge (DBD) as a plasma source because it is easily operated at atmospheric pressure and near-ambient temperature, using a broad range of frequencies and energy densities [9]. In contrast to the combustion-related works referenced above, we use an NTP to activate a hydrocarbon fuel alone, before it is mixed with air and combusted. Normally, combustion relies on large air/fuel ratios; which requires considerably more power to achieve a moderate-to-high plasma energy density for the 'activated' fuel component, than activating the fuel alone. Activating the air component does produce some 'active' species like Oatoms, N-atoms, ozone, and excited molecular oxygen and nitrogen. However, it has not been determined if these species contribute as strongly to combustion enhancement as do smaller, fragmented, excited-state, and free-radical species derived from hydrocarbon 'activation'.

In this paper, we discuss some basic concepts of fuel activation and how we have applied DBD-driven NTPs

to the fragmentation of hydrocarbons; increasing flame stability (viz., for lean-burn conditions), increasing flame speed, and improving fuel consumption.

#### II. FUNDAMENTAL BACKGROUND

#### A. Conceptual Framework

Conventional combustion of hydrocarbon-fuel/air mixtures typically begins with spark ignition, whereby a spark thermally decomposes hydrocarbon and air molecules to produce free radicals and other reactive species. Burning then continues by subsequent reactions of the reactive species generated by the heat released by the combustion process. The overall rate of combustion is usually determined by how efficiently new reactive species are generated in the propagating flame front. However, this sort of self-generation of reactive species is sometimes insufficient to sustain combustion, particularly under lean-burn conditions.

NTP 'activation' does not rely on the self-generation of reactive species. Two possible mechanisms for fuel cracking and fuel activation (creation of more reactive species) exist. The first is based on electron-impact processes, such as dissociation, dissociative ionization, vibrational excitation, and electronic excitation of the parent fuel molecule, which produce molecular fragments, radicals, or excited states relevant to the promotion of combustion reactions. The second mechanism is ion-molecule reactions, in which ions created by electron impact react with neutral gas species and produce species which can promote combustion reactions.

### B. Sample Electron Impact Reactions

Some possible electron impact dissociation reactions for two example hydrocarbons (ethane  $C_2H_6$ , structure CH<sub>3</sub>-CH<sub>3</sub>, and propane  $C_3H_8$ , structure CH<sub>3</sub>-CH<sub>2</sub>-CH<sub>3</sub>, are illustrated below. The most probable reactions for 'cracking' or fragmentation into smaller molecules are cleavage of single carbon-carbon bonds, producing methyl (CH<sub>3</sub>) radicals; or the more energy-intensive

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cleavages of carbon-hydrogen bonds, which can produce CH• radicals, methyl radicals, methylene/carbene radicals (H<sub>2</sub>C:), and hydrogen radicals (H•), or electronic excitations producing excited-state molecule and molecular hydrogen (H<sub>2</sub>).

 $\begin{array}{l} {\rm e} + {\rm C}_2 {\rm H}_6 \, \to \, 2{\rm CH}_3 \bullet + {\rm e} \\ {\rm e} + {\rm C}_2 {\rm H}_6 \, \to \, {\rm H}_3 \bullet + {\rm CH}_2 : + {\rm H}_{\bullet} + {\rm e} \\ {\rm e} + {\rm C}_2 {\rm H}_6 \, \to \, {\rm CH}_{\bullet} + {\rm CH}_3 \bullet + {\rm H}_2 + {\rm e} \\ {\rm e} + {\rm C}_2 {\rm H}_6 \, \to \, {\rm C}_2 {\rm H}_4 * + {\rm H}_2 + {\rm e} \\ {\rm e} + {\rm C}_3 {\rm H}_8 \, \to \, {\rm C}_2 {\rm H}_5 \bullet + {\rm CH}_3 \bullet + {\rm e} \\ {\rm e} + {\rm C}_3 {\rm H}_8 \, \to \, 2{\rm CH}_3 \bullet + {\rm CH}_2 : + {\rm e} \\ {\rm e} + {\rm C}_3 {\rm H}_8 \, \to \, 2{\rm CH}_3 \bullet + {\rm CH}_2 : + {\rm e} \\ {\rm e} + {\rm C}_3 {\rm H}_8 \, \to \, {\rm C}_3 {\rm H}_7 \bullet + {\rm H}_{\bullet} + {\rm e} \end{array}$ 

From the above sample reactions, one can see that the greater the degree of cracking, the higher the concentration of reactive species and, in general, the greater the species reactivity (e.g., carbenes). The more the fuel is cracked/activated, the faster the combustion rate because smaller species normally burn faster.

Under electron impact, ethane and propane are also likely to be ionized into multiple species and these species then further fragment into smaller molecular ions [10].

 $e + C_2H_6$ ,  $C_3H_8 \rightarrow$  Multiple ion species,  $C_xH^+_{2x+2} \rightarrow C_mH_n + + M$ ,

where x, m, and n are integers and M is a neutral molecule. When ionic recombination and/or charge transfer reactions follow dissociative ionization, smaller, more easily-combusted molecular fragments result.

# C. Sample Secondary Reactions

Radicals formed in the above processes can then further dissociate ethane and propane, or their decomposition products, to yield additional fragments and active species, as shown below.

 $\begin{array}{l} {\rm H} \bullet + {\rm C}_{2}{\rm H}_{6} \to {\rm C}_{2}{\rm H}_{5} \bullet + {\rm H}_{2} \mbox{ or } {\rm CH}_{3} \bullet + {\rm CH}_{4} \\ {\rm H} \bullet + {\rm C}_{3}{\rm H}_{8} \to {\rm n} {\rm -C}_{3}{\rm H}_{7} + {\rm H}_{2} \mbox{ or } {\rm C}_{2}{\rm H} + {\rm H}_{2} \\ {\rm H} \bullet + {\rm C}_{2}{\rm H}_{2} \to {\rm C}_{2}{\rm H}_{3} \mbox{ or } {\rm C}_{2}{\rm H} + {\rm H}_{2} \\ {\rm H} \bullet + {\rm C}_{2}{\rm H}_{4} \to {\rm C}_{2}{\rm H}_{5} \bullet \mbox{ or } {\rm C}_{2}{\rm H}_{3} + {\rm H}_{2} \\ {\rm H} \bullet + {\rm C}_{2}{\rm H}_{4} \to {\rm C}_{2}{\rm H}_{4} + {\rm H}_{2} \mbox{ or } {\rm 2}{\rm CH}_{3} \bullet \\ {\rm CH} \bullet + {\rm C}_{2}{\rm H}_{4} \to {\rm C}_{2}{\rm H}_{4} + {\rm H} \bullet \\ {\rm CH} \bullet + {\rm C}_{2}{\rm H}_{4} \to {\rm C}_{3}{\rm H}_{2} + {\rm H}_{2} + {\rm H} \bullet \mbox{ or } {\rm C}_{2}{\rm H}_{2} + {\rm CH}_{3} \bullet \\ {\rm CH} \bullet + {\rm C}_{2}{\rm H}_{4} \to {\rm C}_{3}{\rm H}_{2} + {\rm H}_{2} + {\rm H} \bullet \mbox{ or } {\rm C}_{2}{\rm H}_{2} + {\rm CH}_{3} \bullet \\ {\rm CH} \bullet + {\rm C}_{3}{\rm H}_{8} \to {\rm Products} \mbox{ (e.g., } {\rm C}_{3}{\rm H}_{6} + {\rm CH}_{2} : + {\rm H} \bullet ) \\ {\rm CH}_{2} : + {\rm C}_{3}{\rm H}_{8} \to {\rm CH}_{3} \bullet {\rm r} \mbox{ or } {\rm CH}_{3} \bullet + {\rm C}_{2}{\rm H}_{5} \bullet \\ {\rm CH}_{2} : + {\rm C}_{3}{\rm H}_{8} \to {\rm CH}_{3} \bullet {\rm r} \mbox{ or } {\rm CH}_{4} + {\rm iso-C}_{4}{\rm H}_{10} \\ {\rm CH}_{3} \bullet {\rm C}_{3}{\rm H}_{8} \to {\rm CH}_{4} + {\rm n}{\rm -C}_{3}{\rm H}_{7} \bullet {\rm or } {\rm CH}_{4} + {\rm iso-C}_{3}{\rm H}_{7} \bullet \\ \end{array}$ 

The unstable, excited-state ethylene molecule can then further decompose into acetylene  $(C_2H_2)$  and molecular hydrogen  $(H_2)$ .

 $C_2H_4^* \rightarrow C_2H_2 + H_2$ 

In addition to the above reactions, the other mechanism to be considered for fragmentation or active

species formation is ion-molecule reactions which, for combustion relevance, typically involve charge transfer reactions with negative oxygen ions (typically formed in electric discharges in air) to form hydroxyl (OH) radicals, which can promote combustion chain reactions.[11].

The detection and identification of radical species arising from the decomposition of pure hydrocarbons is a difficult task and such studies have been sparsely reported in the literature. Recently, laser diagnostic techniques (e.g., laser-induced fluorescence – LIF) have been applied to detect hydroxyl (OH) radicals in admixtures of hydrocarbon fuels in air [8]. In the future, such techniques will need to be applied to atmosphericpressure-plasma-activated pure hydrocarbon fuels for the identification of radicals pertinent to combustion.

The results of experiments discussed in this paper, followed by plasma chemistry modeling and further diagnostics of stable and intermediate species will be needed to lend further insight into the dominant processes of plasma-assisted combustion (PAC).

#### III. EXPERIMENTAL TECHNIQUE

# A. General Experimental Setup

Figure 1 shows a block diagram of a typical experimental setup for our two types of PAC investigations: (1) plasma decomposition/'cracking' of hydrocarbon gases, and (2) properties of flames when hydrocarbon fuels are 'activated' by a DBD-generated NTP. Both types of experiments use similar diagnostic, analytical-chemistry instruments.



Fig. 1: Block diagram of typical DBD, non-equilibrium plasma-assisted combustion experimental setup.

The dashed line from the reactor in Figure 1 shows the route of plasma-activated gases under non-combustion conditions ('cracking'), while the solid line to the flame region refers to flame studies. Again, we emphasize that in our experiments the oxidizing gas (i.e., air) is not activated – only the fuel is treated by the plasma reactor. When flames are employed, air is mixed with the fuel gas after it is activated by the plasma.

# B. Plasma Reactors & Instruments

In our usual experiments, we employ a coaxial, cylindrical DBD reactor that processes pure hydrocarbon

gas at local-Los Alamos, ambient pressure (77.3 kPa, because of the Laboratory's altitude of  $\sim 2200$  m) and near-ambient temperature. DBDs, being sources of NTPs, do not considerably raise the process gas temperature – the deposited electrical energy mainly goes into chemical decomposition and molecular excitation – not heat/enthalpy. We used two different types of DBD reactors for our investigations: one for cracking and flame propagation (speed) observations and another for lean-burn flame operation and exhaust-gas species determination.

An artist's rendering of a typical coaxial reactor used for cracking experiments is shown in Figure 2. A similar reactor is used for flame studies, but using an exhaust-gas collector displaced above the top of the reactor (where a flame appears). In both reactors, a grounded tubular inner electrode (diameter 9.5 mm) is centered inside a fusedsilica, dielectric-barrier tube (inner diameter 13 mm and wall thickness 3 mm). Hydrocarbon gas flows through the annular space (1.75 mm gas gap) between the inner electrode and the inside of the fused silica tube. The fused-silica tube is surrounded by a 120-mm high, cylindrical, metal outer electrode (a copper-mesh screen bounded by copper 'corona' rings), which is connected to a high-voltage, alternating current transformer. For leanburn flame operation and flame exhaust-gas species determination, coaxial reactors, similar to Figure 2, but using a solid outer conductor and an alumina-ceramic dielectric tube, were employed. In these cases, air flows through the inner, 'ground' electrode tube and then mixes with the NTP-activated hydrocarbon gas that flows in the



Fig. 2: Illustration of DBD reactor for 'cracking' studies.

annular space.

Electrical power is applied to the hydrocarbon-gas gap (by a high-voltage source connected to the outer electrode) and, when the electrical breakdown voltage is exceeded, a plasma is formed in the gas, thus activating and decomposing it. Figure 3 shows a circuit schematic diagram for the setup.



Fig. 3: Circuit schematic diagram for DBD reactor setup.

The stable decomposition products or flame-exhaust products can be detected with a gas chromatograph, mass spectrometer, or FTIR. In the near future, experiments will be carried out to determine the intermediate (unstable) reaction products.

The electrical power supply consists of a function generator, which supplies a low-voltage sinusoidal signal to an AC amplifier, which in turn drives a high-voltage transformer. This produces a voltage of order 7 - 15 kV on the outer, metal-mesh or solid electrode. The breakdown voltage for some hydrocarbon gases can be obtained from the paper by Heylen [12]. For gas gaps ~ 1.5 mm, ambient pressure of  $\sim 0.77$  atm, and ambient temperature of about 23 C, the breakdown reduced electric field in the gas gap is approximately E/N = 130Td for methane, 163 Td for ethane, and 105 Td for propane. Two different transformers are normally employed to drive the DBD reactor: the first operates in a lower-frequency regime (10's Hz - 1 kHz), while the second operates in a higher-frequency range (5 - 20 kHz). The applied frequency is tuned to match the impedance of the DBD reactor, depending on which gas is employed. The reactor voltage is monitored with a high-voltage probe. The charge transferred through the reactor is monitored by measuring the voltage on a capacitor connected in series to the transformer ground. These two voltage signals are delivered to an oscilloscope, which interfaces to a data acquisition/data processing computer.

The power deposited into the plasma is determined from these two measured voltages, using Lissajousdiagram techniques (charge-voltage plot), as originally developed by Manley in 1943 [13] and later described by Rosenthal and Davis [14], and a computer data-analysis program. The plasma specific energy  $\varepsilon$  (energy per unit volume) is obtained by dividing the deposited electrical power P by the process gas flow rate Q

# $\varepsilon = P/Q$

The specific energy is usually expressed in units of joules per liter (J/L).

#### C. Experimental Results

### 1) Decomposition/Cracking Experiments

Our first experiments on NTP-aided combustion [15] were carried out using activated-hydrocarbon/air flames.

To understand the mechanisms of our observed results, attempts were made to identify the activated fuel species. We have conducted experiments on the cracking of methane, ethane, propane, and butane – results of which are summarized below.

In methane, propane, and butane tests in the absence of a flame, a closed coaxial reactor was used (not illustrated here). This reactor employed an alumina ceramic dielectric tube and metal 'ground' (inner) and highvoltage (outer) electrodes and was of similar radial dimensions to the illustrated reactors. Some air co-flow was sent through the inner electrode. Plasma-treated effluent gas was collected at the end of the reactor (where the activated hydrocarbon gas was mixed with co-flow air) and then sent to a mass spectrometer (MS) for analysis. For both propane and butane (see Figure 4), there is a substantial increase in the normalized MS signal for the lower mass peaks M = 15, 26, 27, and 29; but only M = 15 and 16 show a significant increase for methane.



Fig. 4: MS plot for DBD- 'cracking' of butane (top to bottom: M=16, 2, 26, 30), relative to M=2.

For all three gases (CH<sub>4</sub>, C<sub>3</sub>H<sub>8</sub>, C<sub>4</sub>H<sub>10</sub>), there is a slight increase in M = 2 (assumed to be H<sub>2</sub>), which reinforces our notion that the dielectric-barrier discharge behaves like a fuel-molecule decomposer, rather than a fuel converter [16]. For ethane, the reactor shown in Figure 2 was employed and a gas chromatograph was used to analyze the decomposition products. Figure 5 shows a representative chromatogram ( $\varepsilon = 2400$  J/std lit).



Fig. 5: Gas chromatogram showing major products resulting from the plasma 'cracking' of ethane.

It appears that these fuel gases are decomposed (cracked) by plasma electron-impact collisions that produce smaller, more easily-combustible fragments and, possibly, free radicals that can propagate combustion reactions [11]. The results of our cracking studies appear to support that assumption.

# 2) Lean-Burn/Blowout Experiments

This section summarizes some experiments, as further discussed by Kim et al [17], Rosocha et al [15, 18], and Stange et al [19] et al, on the influence of plasma excitation on the blowout limit of an activatedpropane/air flame (i.e., ultra-lean-burn conditions). For these studies, the experimental setup shown in Figure 1 and a ceramic-dielectric, coaxial DBD reactor were used. As in the reactor of Figure 2, in the employed lean-burn reactor, air flows through the 'ground' tubular inner electrode and propane flows through the annular gap between the inner electrode and an alumina ceramic tube (substitute ceramic for quartz, as in Figure 2). This configuration, with the air surrounded by fuel, is called an inverse flame. The ceramic tube is surrounded by a cylindrical, solid metal outer electrode (as opposed to the screen electrode in Figure 2), which is powered by a HV AC transformer, with applied AC frequency tuned to about 450 Hz, to match the impedance of the propane DBD. As previously mentioned, power is applied to the propane but not the air, activating the fuel alone (in the annular region between the center-ground electrode and the ceramic-dielectric tube). The inner electrode is shorter than the ceramic tube, so there is a region (of variable length, but generally < 1.5 cm) where the fuel, coming from the plasma-activated annular region, and the air, coming through the center ground-tube, partially mix before being ignited at the top of the mixing region.

Blowout tests were conducted by holding the propane flow (through the annular region) constant and increasing the air flow rate (through the inner ground-tube) until the flame blew out. The blowout air flow rate is an indicator of flame stability, and a high blowout air flow rate shows that combustion continues to occur under lean-burn conditions. Most notably, the strongest plasma effect is increased stability at large air flows. Figure 6 [17] shows the minimum blowout air flow rates vs propane flow of an inverse, partially-premixed flame for propane flow rates between 0.2 and 0.8 std lit/min. The results are parameterized according to a standard combustion metric, the equivalence ratio  $\phi$ , for propane-air combustion.

$$\phi = 15.6 \cdot (Q_p/Q_a) \cdot (\rho_p/\rho_a) ,$$

where  $Q_p$  and  $Q_a$  are the propane and air volume flow rates and  $\rho_p$  and  $\rho_a$  are the densities of propane and air, respectively. In the absence of plasma, the blowout limit of a propane flame increases with the propane flow rate and begins to saturate at 0.6 std lit/min propane. When a 10-W plasma is applied to the fuel, the blowout limit shows a large increase for low propane flow (low equivalence ratio). However, the plasma benefit decreases as the propane flow increases, and for propane flow > 0.6 std lit/min the blowout rate actually decreases in the presence of plasma. This is not necessarily detrimental, because low-equivalence-ratio systems show large decreases in pollutant production, especially  $NO_x$ , and are of significant, timely interest.



Fig. 6: Plot of blowout air flow rate versus propane flow rate for a partially-premixed propane-air flame, with and without the propane being 'activated' by a DBD-driven plasma [17].

In this experiment, the discharge power was held constant (10 W) while the propane flow rate was increased. Thus, the discharge energy density  $\varepsilon$ , decreased as the propane flow rate increased (e.g., at  $Q_p = 0.3$  std lit/min,  $\varepsilon = 2$  kJ/std lit, while at  $Q_p = 0.8$  std lit/min, the  $\varepsilon$ -value fell to 0.75 kJ/std lit). Therefore, the magnitude of the discharge energy density seems to affect the blowout limit of a propane flame. In the future, more experiments will be performed to correlate the combustion enhancement with the discharge energy density.

#### 3) Flame-Speed Experiments

Here, a reactor similar to that shown in Figure 2, and operated in a similar fashion to the experiment described above, was used. The ends of the electrodes and the end of the quartz tube were separated by a 6 cm mixing region. By using a relatively long mixing region, we were able to eliminate direct effects of the electric field on the flame. The air- and propane-flow rates were set to 4.6 and 0.3 std lit/min, respectively, to fix  $\phi = 1.58$  as the equivalence ratio. For this case, combustion is relatively complete, so the propane should be mostly consumed.

The photographs in Figure 7, as reported by Stange et al [19] detail the propane-air mixing region – the end of the quartz tube is visible at fiducial (1) and the plasma glow at fiducial (2) is the edge of the outer, high-voltage electrode.

The progressively higher-power propane plasma's effect on the flame is shown in Figures 7a-c. Figure 7a shows a propane-air flame in the absence of plasma. The application of even a relatively low-power 4 W plasma, as shown in Figure 7b, improves the flame symmetry, a marker of stability. In both 7a and 7b, the flame propagates upward only, although at an equivalence ratio of  $\phi = 1.58$ , it is theoretically possible for the flame to propagate downward. In this latter case, the flame propagation rate is insufficient to overcome the upward flow of the propane-air mixture. As more power (specific energy) is applied to the plasma, downward propagation becomes increasingly pronounced, as clearly shown in

Figure 7c. The changes in the flame's ability to propagate downward suggest that the flame-propagation rate increases with plasma power (specific energy).

Experiments comparing methane, propane, and butane flame speeds under the influence of an NTP shown that the flame speed increases in the order butane > propane > methane.

The flame propagates more quickly because it is igniting and burning faster. This combustion enhancement may result from the improved cracking of propane, the creation of reactive radicals, or hydrogen generation. As discussed above, all of these factors likely play a role in combustion enhancement, but the relative importance of each is presently unknown. In the near future, we plan to carry out further experiments to better understand the role of reactive radicals.

# 4) Flame-Exhaust Experiments

For studying flame-exhaust species, the dashed-line route in the block diagram shown in Figure 1 was employed [15]. Propane gas is passed through the active, annular region (approximately 14 cm in length) of the ceramic-dielectric, coaxial-cylinder plasma reactor (as in Figure 2, except ceramic tube replaces quartz tube). The plasma-'activated' propane is then mixed with air (which flows through the center-ground tube) and ignited by an electrical spark at the end of the region where the two gases mix. A portion of the exhaust from the burning propane-air mixture is collected by a sampling system and directed to a mass spectrometer (MS), which measures the fractional concentrations of the effluent gas species.

Mass fragments of particular relevance to a propane mass spectrum are atomic masses 26 ( $C_2H_2$ ), 27 ( $C_2H_3$ ), 39 ( $C_3H_3$ ), and 43 ( $C_3H_7$ ). During operation, the flame was ignited and allowed to burn without plasma for two



Fig. 7: Photos showing an increase in flame propagation speed under the influence of a DBD-driven plasma (propane activated by plasma before mixing with air and combusted). a: No plasma, b: 4W, c: 10W.

minutes. Then the power supply was turned on, and the activated fuel burned for two minutes. This procedure was repeated several times, in order to test the repeatability of any enhanced combustion provided by the plasma. Figure 8 [15, 18] shows typical data (with one mass fragment of propane, M = 43 shown, along

with plots for the expected combustion products M = 18, water and M = 44, carbon dioxide).



Fig. 8: Mass spectrogram of exhaust from an DBD-plasmaactivated-propane/air flame. The traces show: A - at first, propaneair flame (flame on), B: propane-air flame with plasma (activation on/off for two cycles), C: Then flame extinguished (off). The grayshaded regions emphasize where the plasma is turned on.

The partial pressures of the propane fragments decrease while water and carbon dioxide (both common hydrocarbon combustion products) increase when the plasma is turned on (refer to first two gray-shaded regions in Fig. 8). The plateaus at the end of the traces are the result of extinguishing the flame (last gray region) - these are the partial pressures in the absence of any combustion. It is clear that the plasma significantly decreases the partial pressure of unburned hydrocarbons, indicating that propane is being burned more completely with plasma activation. Future experiments are expected to be conducted to examine how changes in plasma energy density affect unburned hydrocarbons, other products of combustion of relevance to pollution (e.g., CO and  $NO_x$ ), the production of combustion intermediate species, combustion temperatures, and the spatial of flames under characteristics plasma-activation conditions.

#### IV. SUMMARY

Hopefully, this paper has given some insight into how NTPs can beneficially influence combustion processes. The potential applications are quite broad, ranging from ignition to flame stabilization, to pollution reduction and increased fuel-utilization efficiency. Even though plasma-based combustion has been studied for many decades, the field of plasma-assisted combustion is still in a nascent state. Proof-of-principle works have demonstrated promising results for gaseous fuels, but more research and development must be carried out to understand the basic combustion-enhancement mechanisms and optimize the process. If applications to other fuels (e.g., gasoline, diesel, jet fuel) are successful, NTP-assisted combustion may prove to be highly beneficial to the energy-usage and pollution-reduction needs of modern society.

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