Electric Field Effects on Premixed Methane-Air Flames in Millimeter-Scale Channels

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1 Background

The influence of electric fields on combustion has been studied since the late nineteenth century. As early as 1899, it was known that electric fields could be utilized to modify flame geometry, as reported by Chattock [1]. Since that time, a number of the effects induced by electric fields on flames have been investigated, including premixed flame speed modifications [2-10], flame blowoff flow rate changes [11-13], variations in flame stability [14], and alterations to emissions [15-17]. Numerical models have been created to model and simulate these effects in the pursuit of better understanding of the phenomena [18, 19]. A commonly referenced explanation for the influence of electric fields on flame behavior is ionic wind, where charged ions and electrons within the flame sheet are impacted by the presence of an electric field. The enhanced motility of these ions and electrons in the direction of the electric field applied. Alternate theories and experiments suggest that energy may be directly applied to flame fronts by electric means [20-22], particularly examining the enhancement of flames by very high frequency (MHz to GHz) electric fields.

The electric field effect on quenching distance seems to be a particular focus area that is missing from the literature. It may be that the quenching diameter was assumed to be inversely proportional to the flame speed, which would reduce the necessity for such a study. Flame phenomena on the millimeter scale are of great concern in the field of miniature combustion and power generation systems. The high energy density of hydrocarbon fuels make them an attractive alternative to batteries for portable power [23-26] but development of such systems is greatly complicated by heat losses leading to quenching [26-28]. In addition to problematic heat losses, some miniature combustor designs exhibit inherent instabilities [29,30], the ability to rapidly modulate the combustion process by electric means may provide novel means by which to mitigate oscillations and regain control of otherwise unstable process. If the observed electric enhancement of combustion processes can translate to miniature reactors it may facilitate the design of lightweight power supplies to replace conventional batteries.

The goal of the present work is to study through experimentation the effect of electric fields on the combustion phenomena at the millimeter scale. The results will serve to further clarify the physics of electric-flame integrations and demonstrate potential means to improve miniature combustion processes.

2 Experimental Description

Electric Field Effects on Flames in Channels

A novel experiment was designed and constructed to observe the propagation speed and quenching behavior of downward propagating premixed methane flames in a narrow channel while subject to externally applied electric fields. The apparatus, referred to here as the V-channel channel and shown schematically in Fig. 1, consisted primarily of two opaque Polymethylmethacrylate (PMMA) blocks which formed the walls of the V-Channel. Oriented vertically, these walls created a small gap which gradually decreased from 5 mm the entrance, to 2 mm at the bottom. This 3 mm change occurred over 100 mm in the vertical direction, such that the quenching distance could be precisely determined from location along the channel. Above the linear section was a curved section that allowed the flame to enter the channel smoothly. The opaque PMMA channel walls were 12 mm thick and held between sheets of clear PMMA to enclose the channel while providing optical access. Fuel air mixture was admited through a sealed chamber at the base of the channel. The chamber at the entrance of the channel contained electrodes for spark ignition of the fuel air mixture and was loosely sealed with a plastic diaphragm to readily release the products of combustion.

The channel was operated in two configurations (Figure 1). The first to establish an electric field perpendicular to the direction of flame propagation and the channel walls, the second to establish fields parallel to the direction of propagation. For the perpendicular field configuration, the electrodes were flat aluminum plates 107 mm square held symmetrically around the channel walls at a distance of 25 mm from one another. For the parallel configuration, the electrodes were 90 mm square plate with centrally located 15 mm holes to permit the V-channel to pass through. The parallel plates were always spaced 25mm apart and were repositioned along the length of the channel to establish the electric field at different locations.



Figure 1. Diagram of perpendicular and parallel field configurations and an image from experiments

In both configurations, the electrodes were energized using a 20 kV 60Hz alternating current transformer, producing a peak electric field of 800kV/m. Due to atmospheric breakdown and arcing, it was not possible to use higher fields.

Flame propagation occurred under quiescent conditions. Prior to each test the channel and chambers were purged with the desired fuel-air mixture until no fewer than sixty full changes of gas had occurred, ensuring quality of the mixture. The mixture was set using O'Keefe Controls sonic nozzles and Omega pressure gauges.

Results were recorded using a high speed video camera at 2000 fps. Due to the small size and low luminosity of the flame, it was not directly detectable the flames at the desired frame rate. To compensate, the V-channel was placed in a single pass Z-type Schlieren photography system with a radial cutoff and illuminated with a high-intensity light emitting diode (LED).

To extract flame quenching distance and propagation speed prior to quenching, a script was written using the Image Processing Toolbox in MATLAB. The script autonomously enhanced video frames, detected the motion of the flame sheet and mapped pixel values to the known geometry of the V-channel.

Spark ignition of the gas mixture was performed at the top of the test volume. The flame propagated downward, with the direction of gravity, with exhaust gasses being expelled from the top of the test volume. In the perpendicular field configuration, experiments were performed at 5 equivalence ratios ranging from 0.85 to 1.2. In the parallel field configuration, four equivalence rations from .95 to 1.2 were tested. To minimize the impact of environmental factors and variability in mixture, each nominal equivalence ratio and configuration was tested multiple times, alternatively applying electric field and allowing the flame to propagate freely, providing a reference to which the electrically altered flames could be compared. In all cases, 6 tests were run without electric field and 6 were run with electric field. For 1.0 equivalence ratio with perpendicular field and additional 6 tests without field and 6 tests with field were conducted.

3 Results

3.1 Quenching Phenomena

At all equivalence ratios, it was found that the perpendicular field had a detrimental effect on the flame, increasing quenching distance, while parallel fields enhanced the flame greatly reducing quenching distance. For each equivalence ratio but the richest tested, the addition of perpendicular field also increased the variance of the quenching diameter measurement. It is not yet clear whether this was a result of decreased stability in the flame or the periodic nature of the applied electric field.



Figure 2. The influence of 800kV/m on Quenching Distance of methane-air flames. All results normalized by observations at 0 kV/m

Figure 2 displays the data graphically. Each point indicates the mean result of a field/equivalence ratio normalized by the mean value observe in the absence of applied electric field. The patches indicate the standard deviation about the mean value.

There is no variance indicated for the parallel field configuration, because in all test the flame was observed to quench immediately upon reaching the extent of the applied electric field. An inherent limitation of this apparatus is the limited span of the applied parallel field which could at most prevent quenching for 25mm along the length of the channel, reducing quenching distance to no less than .75 mm before the flame exits field.

3.2 Propagation speed

Electric Field Effects on Flames in Channels

Propagation speed is another parameter of the flame that was impacted by the presence of electric field. The propagation speed was estimated for the 75 milliseconds (150 frames of data) immediately prior to quenching. The results are presented in Fig. 3 for both electric field conditions. They show that the perpendicular field moderately lowered the propagation speed while the parallel field greatly increased it. The effect was more pronounced at the stoichiometric mixture fraction and when slightly rich, but the effect was consistently observed over the entire range of mixtures. Assuming charged species are the primary or sole agents by which flames respond to electric fields, one would expect that colder less reactive mixtures (lean and rich) would possess lower ion concentrations and thus be less influenced by electric fields as we have observed.

Similarly to the quenching diameter results, the addition of the electric field increased the spread and standard deviation of the data in all equivalence ratios. Another similarity is that the propagation speeds are clearly separated for all but the lean mixture, and even that mixture maintains a higher average propagation speed with no electric field. Figure 3 shows the data plotted versus equivalence ratio, with mean values and bounded by one standard deviation.



Figure 3. Flame speed versus equivalence ratio for methane-air flames in narrow channels.

4 Discussion

The observed inverse correlation between quenching distance and propagation speed under the influence of electric fields is entirely consistent with classic theory of flame quenching which extinction occurs when heat loss by to conduction to the solid exceeds the chemical heat generation [23]. Commonly quenching distance d_a is expressed as

$$d_q = \frac{k}{S_L C_p} \sqrt{\frac{T_f - T_i}{f(T_i - T_0)}}$$

Depending upon conductivity k, flame speed S_L , specific heat C_p , a geometric factor f, and the temperatures of the flame T_f , ignition T_i and ambient conditions T_0 . From this the proportionality $d_q \sim 1/S_L$ appears. As previously noted, these experiments were not able to resolve the extent to which the parallel electric field would decrease quenching diameter, but the observed propagation speeds would strongly suggest that large reductions would be possible.

The readily observable parameters of quenching diameter and propagation speed do not readily elucidate the mechanism affect such parameters. As others have noted [20], such effects remain a topic of active research. The directional sensitivity observed in the present work indicates that transfer of energy to electrons and ions in the flame, if present, is not dominant. The heating of electrons and proposed kinetic effects should proceed on the molecular scale, independent field orientation. Similarly, the creation of bulk hydrodynamic forces 'blowing' seem an implausible explanation given the confined structure of the apparatus. The remaining intermediate scale of transport phenomena should be considered.

As examined in the context of plasma physics [24], the weakly ionized plasma of a flame sheet naturally develops net neutral flux of electrons and ion species toward their boundaries. Upon application of electron potential, this flux becomes non-neutral corresponding to the preferential transport of charged species. The maximum (saturation) ion and electron fluxes are given by [25]:

$$J_i = n_{\infty} e \sqrt{T_e/m_i} \quad J_e = n_{\infty} e \sqrt{T_e/m_e}$$

With the far field ion density n_{∞} , electron charge *e*, electron temperature T_e and masses m_j . Critically the difference of a factor $\sqrt{m_e/m_i}$ shows a much greater potential for electron loss under imposed voltage than ion loss. A possible explanation for the enhanced quenching phenomena under perpendicular field is that the loss of electrons to the walls constitutes a significant loss of energy or an important source of ionization reactions. Using values of n_{∞} and T_e from [24], and applying the over the thickness of a flame (~3 mm) in an infinitely deep channel, we find a loss current of 10^{12} electrons-m⁻¹. As the flame width (the active region, not including the cold region near the wall) decreases toward 0, this loss term will become increasingly important.

While there will be a similar outward flux of electrons in the parallel field configuration, this does not necessarily constitute a 'loss.' Electrons and ions driven ahead of the flame sheet will only collide with the unreacted mixture, which may serve to initiate reactions ahead of the flame. Satisfactory evaluation of this interaction as well as the effect of flux toward the reacted mixture will likely require rigorous modeling accounting for detailed transport of species and chemi-ionization reactions.

5 Conclusions

In narrow channels, the application of external electric fields strongly affects both the quenching distance and propagation speed. Further this interaction is highly sensitive to the orientation of the field, with a field perpendicular to the direction of propagation moderately impeding the reaction while a field across the flame sheet vastly accelerates the reaction. This behavior was observed across a range of equivalence ratios, although it was somewhat weaker for mixtures far from stoichiometric.

The precise control of flame geometry relative to the applied electric field and the channel wall achieved in these experiments serves to isolate potential physical phenomena responsible for the observed combustion phenomena. Kinetic enhancement and energy coupling theories are inconsistent with the orientation sensitivity and hydrodynamic 'blowing' of flames could not occur significantly across the channel or into the closed end of the chamber. Forced transport of electrons or ions out of the flame sheet would account for the decreased reactivity in the perpendicular field configuration. Similarly, transport of charged species across the flames sheet would increase heat transfer and ionization ahead of the flame, causing the higher flames speeds observed in the parallel field configuration

Future study of millimeter scale combustion under electric fields should include both experimental and modeling efforts. New experimental apparatuses must be developed to support the dramatic enhancement effects observed with parallel fields. The addition of Langmuir probes to measure ion currents to and from flames, and microwave interferometry to measure electron density would provide significant insight into to transport and generation of charged species in the flames. Detailed modeling, in the style of Hu et al. [18] or Belhi [19], would greatly assist in isolating the precise cause of electric-flame interactions present.

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