An experimental and numerical study of flames in narrow channels with electric fields

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Abstract. The advancement of microscale combustion has been limited by quenching effects as flames cease to be much smaller than combustors. The long studied sensitivity of flames to electrical effects may provide means to overcome this issue. Here we experimentally and numerically investigate the potential of electric field effects to enhance combustion. The results demonstrate that, under specific conditions, externally electric fields will sustain combustion in structures smaller than the quenching distance. The analysis proposes a reduced mechanism to model this result and provides a study of the governing parameters. We find good qualitative agreement between the model and experiments. Specifically, the model is found to successfully capture the capacity to increase and decrease flame speed according to electric field magnitude and direction. Further, in both experiments and computations the sensitivity to electrical enhancement increases for more energetic mixtures. We do find that the model underpredicts the maximum achievable speed enhancement observed, suggesting that additional phenomena should be included to expand the range of conditions that can be studied.

1. Introduction

In this paper we examine the use of electrical effects as a means of improving the performance of micro-combustion systems. One of the primary technical challenges in miniaturizing combustors is the phenomenon of quenching, wherein flames are extinguished as heat losses to closely spaced combustor walls become so great that they overcome the rate of chemical release and the combustion reaction can no longer sustain itself [1]. To date, progress has been made in the field of micro-combustion by reducing thermal losses from the flame [2] and by increasing the pressure and reactivity of the fuel-air mixtures [3] to overcome quenching. By introducing new physical processes it may be possible to further reduce the scale of combustion.

As early as 1899, it was known that electric fields could be utilized to modify flame geometry [4]. Since that time, experimental studies have found that electric fields can improve the speed of flames [5, 6]. In the context of quenching, this increase in flame speed corresponds to an increased rate of chemical heat release, and a reduction in quenching. We demonstrate below that an applied electric field will increase the propagation speed of flames at the limit of quenching and that this increases prevents the occurrence of quenching. Further, we describe a basic model to understand the enhancement of laminar flames.

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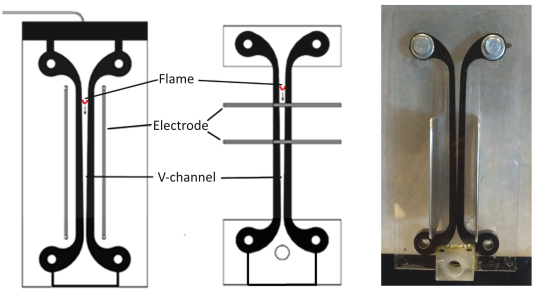

Figure 1: Diagrams of the V-channel for perpendicular (left) and parallel (center) electric fields. Photograph of the V-channel for perpendicular fields (right)

2. Experimental

2.1. Methodology

An experiment was developed to observe the propagation speed and quenching behavior of premixed methane-air flames in a narrow channel while subject to externally applied electric fields. The apparatus, referred to here as the V-channel and shown schematically in Figure 1, consisted of two Polymethylmethacrylate (PMMA) blocks which formed the walls of the V-Channel. Oriented vertically, these formed a gap which decreased from at 5 mm the the entrance, to 2 mm at the bottom over a 100 mm length. The channel walls were 12 mm thick and held between clear PMMA sheets to enclose the channel while providing optical access. The channel was operated in two configurations. One established the electric field perpendicular to the channel walls, the other established a fields parallel to the walls. 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 plates with centrally located 15 mm square holes, to permit the V-channel to pass through. The parallel plates were spaced either 25 mm or 75 mm apart to achieve higher and lower electric field strengths for a given voltage. When spaced 25 mm apart, the plates were positioned along the V-channel such that quenching would occur in the region between them without an applied filed.

Prior to each test the channel and chambers were purged with the desired methane-air mixture until no fewer than sixty full changes of gas had occurred. Results were recorded using a high speed video camera at 2000 fps and a Z-type schlieren system and subsequently processed with an automated cross-correlation algorithm to measure flame propagation speeds. Spark ignition of the gas mixture occurred at the top of the channel. Flames propagated downward while exhaust gases exited from the top of the test volume. In the perpendicular field configuration, experiments were performed at 5 equivalence ratios from 0.85 to 1.2. In the parallel field configuration, four equivalence ratios from .95 to 1.2 were tested. To minimize the impact of environmental factors, 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 conducted with electric field and 6 without. For a 1.0 equivalence ratio with perpendicular field an additional 6 tests with and without field we conducted.

Two high voltage power supplies were used to energize the electrode plates. The first produced an alternating voltage (AC) of 20 kV at 60Hz and was used on both the perpendicular and parallel configurations. In the parallel configuration, this resulted in an electric field of 800 kV/m with 25mm plate spacing and 266 kv/m for 75mm spacing. The second power supply operated at a constant (DC) 4.5 kV, producing 180 kV/m or 60 kV/m, depending on plate spacing. The DC supply was tested under both polarities, such that the electric field lines lay

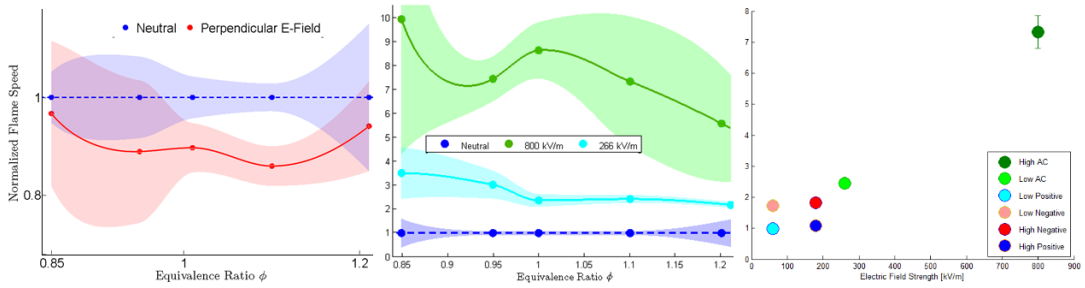

Figure 2: Variaiton in the flame propagation with applied electric field and stoichiometry. **Left:** 800 kV/m AC with perpendicular orientation, **Center:** 800 and 266 kV/m AC in parallel orientation, **Right:** Stoichiometric flames in AC and DC fields with parallel orientation. 'high/low' indicates 800/266 kV/m for AC and 180/60 kV/m DC

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along or against the direction of propagation (referred to as positive and negative, respectively in the left plot of Figure 2). Flame propagation occurred under quiescent conditions.

2.2. Results

The changes in propagation speed with electric field and stoichiometry are presented in Figure 2. Primarily, we observe large increases in propagation speed due to the AC and negative DC fields in the parallel field configuration. The positive DC field showed minimal impact on the propagation speed and the perpendicular AC field produced a small but measurable reduction in speed. For the AC experiments, the degree of enhancement or impairment increased with the electric field magnitude. For those conditions where the fuel concentration was varied, the electric field was most effective at lean and stoichiometric conditions, although large variability in the measured speeds makes it difficult to detect any consistent trend as flames became increasingly lean. In all cases where the propagation speed was enhanced, the flames did not quench until they reached the farthest extent of the electric field, beyond the location at which quenching would have otherwise occurred.

3. Numerical

3.1. Formulation

In this analysis, we consider a lean planar premixed flame propagating with a constant velocity and subject to an electric field parallel to the direction of propagation. The equations describing the structure of this flame in the presence of an electric field begin with the mass and species conservation equations for two-step reaction [7]. Additionally, the model needs to consider the effect that the electric field exerts on the charged species. For the weakly ionized conditions in a flame, these effects may be accounted for by the addition of an electrically induced drift velocity for charged species as well as accounting for variations in the electric field caused by those species. For the full development of this model and a discussion of the assumptions, the reader may consult [8]. For a lean flame which reacts primarily by a two-step reaction with a neutrally charged intermediate, but also includes reactions for ionization and recombination,

the non-dimensional governing equations may be presented as:

$$\frac{d\theta}{dx} = \frac{d^2\theta}{dx^2} + \mu Q\left(\omega_{II} + \omega_{IV}\frac{q_{IV}}{q_{II}}\right) \tag{1}$$

$$\frac{dY_F}{dx} = \frac{1}{Le_F}\frac{d^2Y_F}{dx^2} - \mu\omega_I \tag{2}$$

$$\frac{dY_Z}{dx} = \frac{1}{Le_Z}\frac{d^2Y_Z}{dx^2} + \mu\left[\omega_I - \omega_{II} - \omega_{III}\right] \tag{3}$$

$$\frac{dY_{Z^+}}{dx} = -\mu^{1/2}\frac{d\left(EY_{Z^+}\right)}{dx} + \frac{1}{Le_{Z^+}}\frac{d^2Y_{Z^+}}{dx^2} + \mu\left[\omega_{III} - \omega_{IV}\right] \tag{4}$$

$$\frac{dY_{e^-}}{dx} = \mu^{1/2}\left(\frac{m^+}{m^-}\right)^{1/2}\frac{d(EY_{e^-})}{dx} + \left(\frac{m^+}{m^-}\right)^{1/2}\frac{1}{Le_{Z^+}}\frac{d^2Y_{e^-}}{dx^2} + \mu\left[\omega_{III} - \omega_{IV}\right] \tag{5}$$

with boundary conditions $\theta = Y_Z = Y_{Z^+} = Y_{e^-} = Y_F - 1 = 0$ at $x \to -\infty$ and $\theta' = Y_F' = Y_Z' = Y_{Z^+}' = Y_{e^-}' = 0$ at $x \to \infty$. Where Le, m, θ, Y_F, Y_Z, Y_{Z^+}, and Y_{e^-} are the Lewis number, mass of a charged species, temperature, and mass fractions of fuel, neutral radical, ionized radical and electrons. The remaining variable μ is the dimensionless eigenvalue of the problem which relates to the laminar flame speed S_L by the proportionality $\mu \propto S_L^{-2}$.
The non-dimensional reaction rates are written as

$$\omega_I = \beta^2 Y_Z Y_F \exp\left\{\beta\frac{\theta - 1}{1 + \gamma(\theta - 1)}\right\} \tag{6}$$

$$\omega_{II} = Y_Z \tag{7}$$

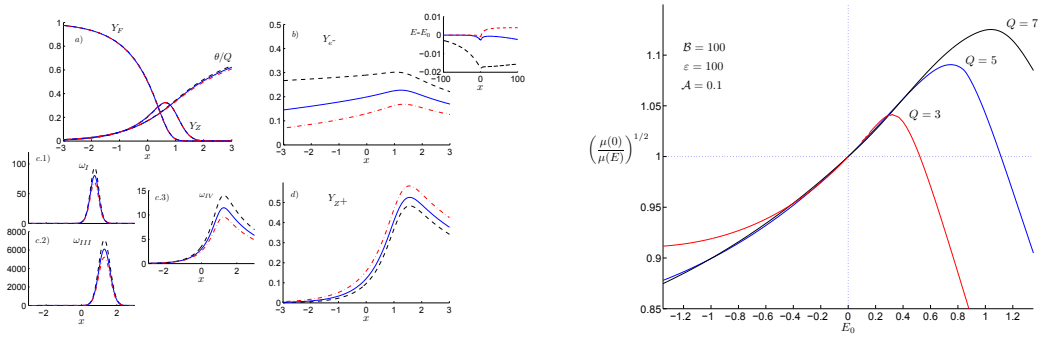
$$\omega_{III} = \beta^2 \mathcal{A} Y_Z \exp\left\{(\beta + \Delta\beta)\frac{\theta - 1}{1 + \gamma(\theta - 1)}\right\} \tag{8}$$

$$\omega_{IV} = \mathcal{B} Y_{Z^+} Y_{e^-} \tag{9}$$

with $\mathcal{A} = \dfrac{A_{III}}{A_I}\dfrac{W_{Z^+}W_F}{W_Z\bar{W}}\dfrac{e^{-\Delta\beta/\gamma}}{Y_{F_0}}$, $\mathcal{B} = \dfrac{A_{IV}}{A_{II}}\dfrac{\bar{W}W_Z}{W_{Z^+}W_F}Y_{F_0}$ and $\Delta\beta = \gamma\dfrac{E_{III} - E_I}{R_g T_c}$ representing the effect of a differential activation energy between the chain-branching and the chemi-ionization steps.
In the above equations, the electric field E is the result of both the externally imposed field E_0 and the two charged species. The spatial variation due the charged species is $dE/dx = \mu^{1/2}/\epsilon(Y_{Z^+} - Y_{e^-})$. This my be integrated, subject to the condition $E(x \to -\infty) = E_0$ to complete the formulation.

3.2. Results

The problem defined by Eqs. (1)- (5), with the corresponding boundary conditions, was solved numerically to compute the eigenvalue μ and the profiles of temperature and species. Figure 3 shows a representative flame structure for neutral conditions as well as for a positive and negative external fields. Fundamentally, the addition of the ionization/recombination reactions serves to delay the heat release, reducing the transfer of heat to the unburnt gases and lowering flame speed. The external electric field is therefore able modify S_L by shifting the relative location at which recombination occurs and heat is generated.
For comparison to our experimental results, it is most illustrative to examine the effects of both E_0 and the heat release parameter Q (which relates to ϕ in the experiments), as shown in the



Flame Structure Flame Speed

Figure 3: **(left)** a) Profiles of fuel Y_F, radical Y_Z and temperature θ/Q, b) and d) Electron and proton mass fraction profiles, c.1) chain-branching reaction rate ω_I, c.2) proton-electron production rate ω_{III} and c.3) proton-electron recombination reaction rate. ω_{IV} for $E_0 = 0$ (blue, solid line), $E_0 = 0.65$ (black, dashed line) and $E = -0.65$ (red dot-dashed lines) with $\beta = 10, \Delta\beta = 1, \mathcal{A} = 0.1, \mathcal{B} = 100$, $\varepsilon = 100$, $m^+/m^- = 100$ and $Q = 5$. The inset of figure 3b) represents the auto-induced electric field created by the charge displacement near the flame. **(right)** The variation of flame speed, $\mu^{-1/2}$ with E_0 and Q.

right of Figure 3. Here we find that flame speed increases with E_0 until a critical value is reached and S_L begins to decrease. The observed critical point occurs when E_0 becomes large enough that it overcomes the auto-induced field, causing separation of the charged species that reduces recombination.

4. Conclusion

The presence of an externally electric field can, under appropriate conditions, enhance millimeter-scale combustion. This can increase the rate of combustion and prevent quenching. Although the full extent to which quenching is prevented has not been determined, the large observed increases in flame speed indicate that significant gains can be realized over conventional combustors. The model demonstrates partial agreement with experiments. Chiefly, it captures the increase in flame speed with positive parallel electric fields and that the enhancement increases with the available energy in the mixture. The predicted decrease in speed for negative parallel fields was not observed in the experiments. Small decreases were found for perpendicular fields, showing that ion transport can be detrimental to the flame, but this is beyond the scope of the one dimensional model. Also the maximum degree of enhancement observed far exceeded predictions. Future efforts will progressively expand this model to include more complex features while remaining elementary enough to provide a clear understanding of the process.

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