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Detailed characterization of DC electric field effects on small non-premixed flames

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ABSTRACT

When drawn from a flame by an electric field, ion and electron collisions with neutral gas molecules influence flame shape, combustion intensity, soot formation, and the ion production rate. We describe these behaviors as they relate to the voltage–current relationship of a coflowing non-premixed methane/air flame. Simultaneous measurements of CH* chemiluminescence and ion current confirm a scaling relationship between these properties at saturation conditions. Separate mechanisms, depending on polarity, adequately explain additional current measured beyond saturation. Finally, flame oscillations observed at the transition to saturation ion current under certain flow conditions suggest a competition between two forces. The reason for this behavior is not clear; however, plausible mechanisms are identified.

1. Introduction

Hydrocarbon flames naturally produce charged intermediate species (chemi-ions and electrons) when burned. Chemi-ions do not participate in major chemical heat release pathways, thus explaining the gap in kinetics data for many of these reactions; however, through experiment, concentrations between 10^9 and 10^{10} ions per cm^3 have been measured for stoichiometric premixed flames [1]. Although, charged species account for a small fraction of all molecules in a hydrocarbon flame, an electric field and the resulting current of ions and electrons can indicate the presence of a flame [2]; can identify the fuel, the flame structure, and the flow rate [3]; and will often signal the onset of flame instability. With respect to actuation, sufficiently strong fields influence flame shape [4,5] and stability [6]; affect soot formation [7–9]; alter burning velocities [10]; force extinction [11]; and produce body forces similar to buoyancy [4,12,13]. Discussed in detail by Lawton and Weinberg [14], most behaviors are accounted for when the observed phenomena are described by ion wind effects alone. An ion wind (or more accurately, an ion-driven wind) is the sum effect of repeated ion collisions with the neighboring neutral gas. One can envision a screen mesh dragged through a pool of water as analogous – where the surrounding fluid eventually acquires a velocity lower than the screen, but in the same direction.

In addition, soot is electrically active; though whether this results from ionic precursors, thermal ionization, charge attachment, or some combination is not clear [15–20]. However, this property may be used to both detect formation and precipitate soot from the reaction zone. Additional applications include ignition and knock sensing in engines [2,21], organic compound detection [23], and semiconductor surface treatments [24].

As seen in the above, the monitoring and simultaneous manipulation of ion trajectories has been proposed as a powerful sensing and actuating platform [22]. However, reaction rate sensitivity and the interdependence of the ion-driven wind and flame structure demand an experimental apparatus sensitive enough to quantify this influence. The following sections describe such an apparatus, along with the interaction between non-premixed flame chemi-ions and any changes in physical structure created by electric field-driven convective flows.

2. Experimental setup

The coflow burner in this study consists of two plenums threaded together. Fuel and diluent enter through the bottom section and pass through a central tube (2.13 mm ID); air, introduced in the top section, exits through a (25.4 mm OD) honeycomb mesh. The central tube and honeycomb mesh are flush with the burner exit, but their extension can be adjusted to create different jet flow boundary conditions. Thermal mass flow sensors report fuel and diluent flowrates, and a rotameter meters air flow.

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Unless otherwise noted, flow rate is reported in standard cubic centimeters per minute (sccm).

A potential difference applied between the burner and a downstream mesh produces an electric field. Combustion gases flow past the mesh's permeable surface limiting any interaction with the flame – however, prior work has shown that when compared to a solid downstream electrode, the influence is negligible as long as the electrode is several flame diameters from the burner [25]. The applied potential, normalized to electrode separation, defines the nominal electric field strength used to describe the results. A positive electric field is defined as electric field vectors directed from the burner to the downstream mesh. The burner and a simplified electrical circuit are shown in Fig. 1.

Ohm's law relates the measured potential drop across a shunt resistor, placed between the burner and supply ground, to ion current. Average current is the mean of at least 1000 samples; error bars represent ±1 standard deviation; and software filters lower the noise floor by removing high frequency power supply fluctuations. In addition to ion current, a narrowband filter (430 nm ± 10 nm FWHM) affixed to a PMT captures CH$*$ emission over a solid angle sufficient to encompass the entire flame.

Images of fluorescent acetone (PLIF) seeded in the coflowing air stream help determine the role of ion driven winds on air entrainment. The small amounts of seed acetone vapor and its carrier gas (nitrogen) did not affect ion current measurements. The 4th harmonic of a Nd:YAG (266 nm) light source is shaped to illuminate the flame's cross section; the resulting fluorescence as the vapor attempts to equilibrate is captured by an orthogonally-placed ICCD camera (Fig. 2). Acetone's short relaxation time and camera gating features permit temporal filtering of scattered light, thereby attenuating flame luminosity in the final image. Signal strength is determined by the light absorbed, laser illumination intensity, molecular cross section, light collected, and fluorescence efficiency [26–28].

Prior to each test, the burner is inspected for soot buildup. The electrical nature and low work function of soot can affect the average mobility of charge carriers; alter regions where electrical forcing takes place; and modify kinetic pathways, which might influence ion formation. The uncertain role of soot is one of the challenges when comparing electrical effects across different fuels and configurations; therefore, the presented experiments take care to limit the impact of soot on all measurements.

3. Results

Qualitatively, an electric field directed toward the burner surface increases flame width and decreases flame height – driven by positive ion drift and net ion wind toward the flame base (Fig. 3). By varying field strength, the flame's luminosity gradually increases – peaking at approximately 0.8 kV/cm – it then dims, and finally increases once again. Both ion current and flow field images as seen in later figures display similar non-monotonic trends.

Regardless of polarity, ion current as a function of electric field displays three distinct regions (Fig. 4):

Subsaturation – Ion current responds parabolically with increasing applied field strength. Ion production rate in the flame exceeds the removal rate by the field. Recombination is diminished as field strength increases, rendering kinetic pathways, associated with ion recombination, irreversible. The resistivity of the electrode gap affects the slope of the curve.

Saturation – Changes in ion current with applied voltage are negligible. The applied electric field, at this point, removes all ions from the flame zone. An analog to this behavior can be found in the arc discharge literature. Ion current at saturation scales with carbon flux [3] even with small levels of dilution (Fig. 4). Flame temperature is not far different for diluted fuels because flame location is determined by regions where heat

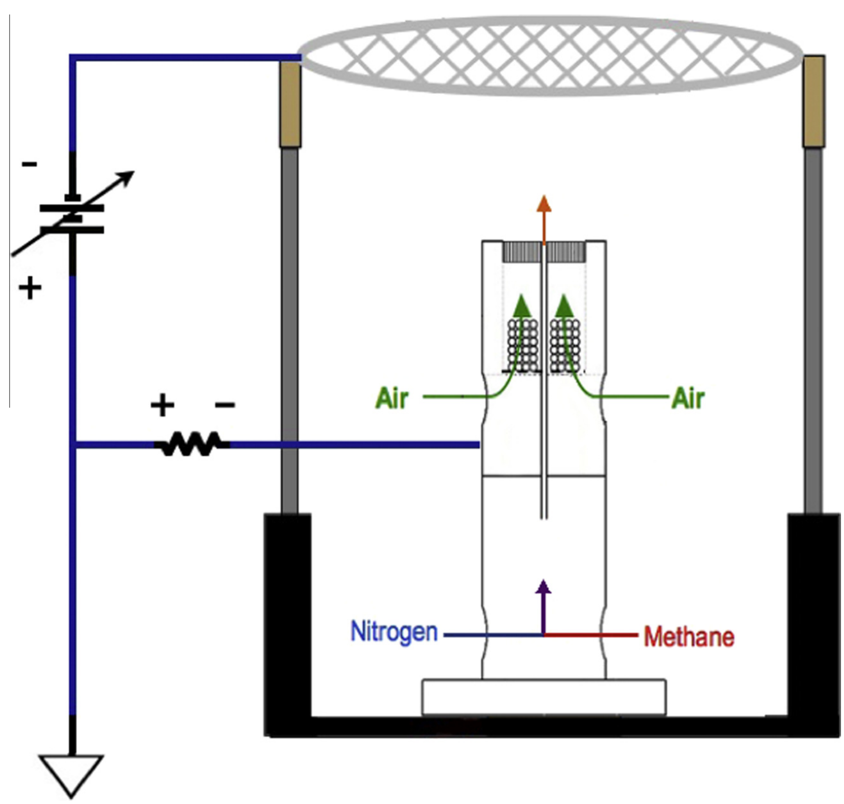

Fig. 1. The above cartoon shows the effective electrical circuit used in ion current measurements and the internal construction of the burner.