Simulated Gravity Using Electric Fields in Microgravity Combustion

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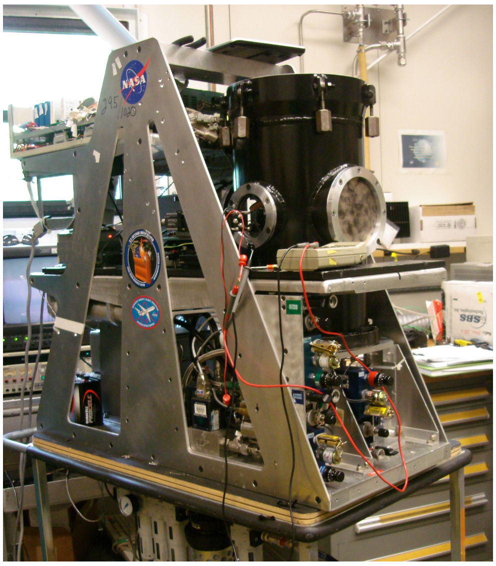
1 Introduction

The objective of this study is to improve the understanding of flame behavior under the influence of electric fields. When applied to a flame, an electric field can produce an ion-driven body force, through collisions with neutral molecules, that is similar to the way that gravity can direct less dense gas via buoyancy. Depending on the field strength, this electrically driven body force can potentially alter flame stability [Belhi et al., 2010, Sher et al., 1993], induce convection [Papac, 2005], and simulate microgravity [Papac et al., 2003, Papac and Dunn-Rankin, 2006, Strayer et al., 2002]. The small concentration ($\approx$ 10 parts per billion) of charged species make chemical effects an unlikely explanation for the observed behavior. Instead, effects are generally attributed to the ion wind, an action-at-a-distance effect, which can alter a flame's behavior and can be used as a localized actuator. Once an electric field is applied across the flame zone, ion acceleration due to Coulomb forces is limited by collisions with local neutral molecules. The ion kinetic energy is repeatedly lost and gained by collisions with neutral molecules and the work performed by the electric field, respectively; this process results in ions and neutral species traveling at nearly constant, but different, average velocities toward the electrodes.

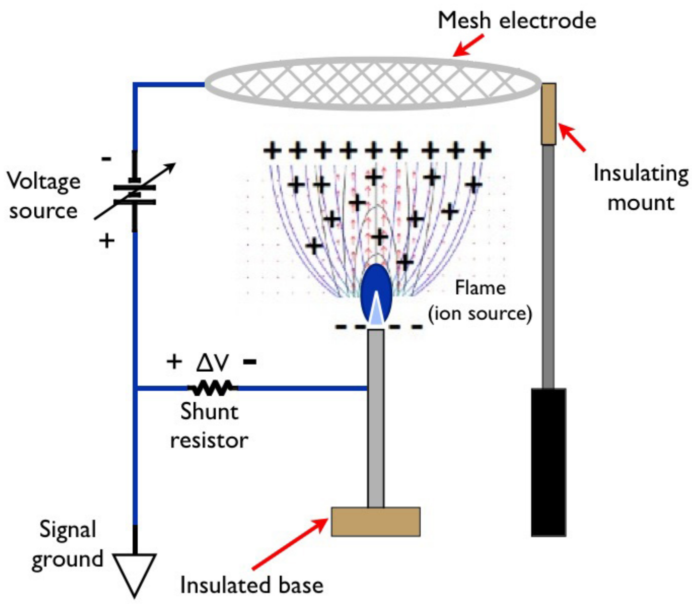
In a 1g environment, the plume of hot gases from a flame naturally induces, through mass continuity, a convective flow to the neighboring cooler environment, giving rise to the flame's egg-like shape. In a microgravity environment, buoyant convection, which is mainly responsible for the transport of fresh oxidizer to a flame, is removed and the influence is mainly driven by molecular diffusion and the initial momentum of the jet [Ross, 2001]. A number of experiments [Yuan and Hegde, 2003, Yamashita et al., 2008, Carleton and Weinberg, 1987] have studied the influence of an electric field in microgravity environments to measure mobility, the influence of an electric field on burning rate constants, and the feasibility of inducing convection in a buoyancy free environment. The following described work compares a jet flame under the influence of an electric field in 1g and μg using the NASA 2.2-s Drop Tower to identify the roles of two transport mechanisms, buoyancy driven convection and ion wind driven convection, in controlling flame shape.

2 Experimental Setup

The experimental drop rig (Fig. 1(a)) includes a cylindrical test chamber (24.6 cm i.d.$\times$ 53.3 cm length), flow system, and data acquisition/control hardware. The burner is a stainless-steel fuel tube (2.1 mm i.d., 2.4 mm o.d.), coaxially positioned inside the cylindrical test chamber. Gas flow was controlled with a fixed orifice and upstream pressure. The average jet velocity was 27 cm/s in all cases, corresponding to a 0.05 SLPM volumetric flow rate. A hot-wire igniter (coiled 29-gauge Kanthal, 11 cm length), which can be positioned over the burner by a rotary solenoid, is used to ignite the fuel (CH_4, 99.97%). Data signals from thermocouples, pressure transducers, and a tri-axis accelerometer (Crossbow, CXL02TG3-S) are digitized and recorded at 100 Hz. The flame is observed by a CCD color camera (Hitachi HV-D30), transmitted through a tethered optical fiber, and recorded using a digital/analog video cassette recorder placed atop the Drop Tower.



(a) NASA Glenn 2.2-s. Drop Rig



(b) Electrical schematic

Figure 1: Experimental Setup

In the drop experiment, fuel flows are introduced to the burner (t = -8 s) prior to the drop event (t = 0) to establish a steady flow through the flow orifice. Following ignition and igniter retraction, a selected high voltage is applied to the mesh electrode relative to the burner. The mesh electrode is positioned 5 cm above the tube exit. Ion current is computed by measuring the voltage drop across a 1 MΩ resistor in the high-voltage return line using a signal conditioning module (Dataforth SCM5B41). The gas flows and applied voltage are shut off at the impact (t = 2.2 s) of the rig on the inflated air bag at the bottom of the Drop Tower.

3 Results

The similar influence of buoyant convection and the ion-driven wind make it difficult to decouple their individual effects in a 1g environment. With the use of the 2.2-s Drop Tower, the following results explore the relevant physics of a gravity free, electrically manipulated flame. Images (Fig. 2) extracted from video taken under different gravity and voltage conditions show steady state flame shapes, with the exception of the μg flame with no voltage applied, which required a longer settling time than the drop tower allowed. Without external influences, a μg jet flame with a low initial momentum will take on a near spherical shape owing to the lack of a preferential transport direction of products; whereas on Earth, buoyant convection directs hot products along the gravity vector. When an electric field is applied, the resulting ion wind drives away combustion products, much like buoyancy, and entrains air to the reaction zone.

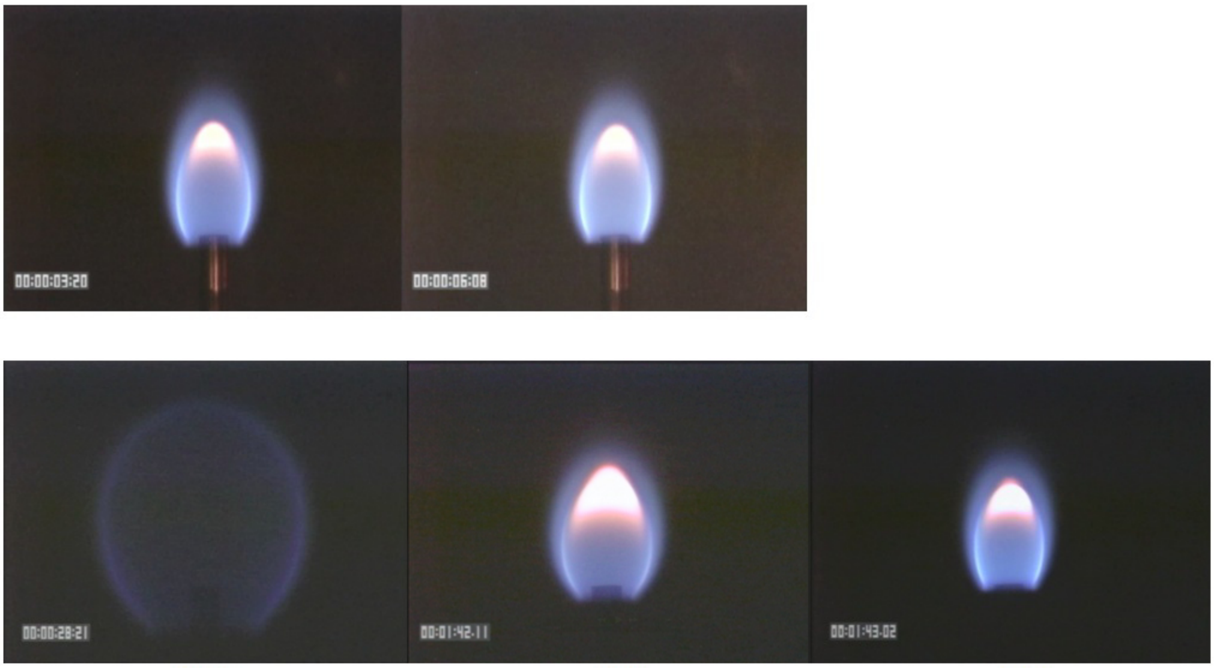


Figure 2: Flame images under different gravity levels and applied mesh voltages.

Figure 3 shows that ion current as a function of applied voltage (V-I curve) is similar regardless of the gravity level. The ion current exhibits a minor difference in magnitude when changing gravity levels with an upward directed field (negative applied potential), whereas a downward directed field applied in μg forces the flame against the burner tube, partially quenching it, thereby reducing the ion current (Fig. 4).

4 Discussion

Relative contributions of gravity and the electric field to flame shape were compared by taking the absolute difference between microgravity images with an applied field and 1g flame images without an applied electric field and computing the RMS of the entire differenced image. When used for image comparison, the RMS metric is a quadratic mean that assumes that a reference image is known, in this case the 1g flame, and that the μg flames are distorted versions of the reference. The lower the computed RMS value, the more similar the images. Differences in soot luminosity were not evaluated because of pixel saturation. Future work should include the use of a filter to normalize the color channels, improving future comparisons. Both the images and computed RMS values show the closest match to be between the microgravity flame with -5 kV applied and the 1g flame. The applied potential over a 5 cm separation corresponds to a 1 kV/cm mean applied field strength. Carleton et al. [1998] observed

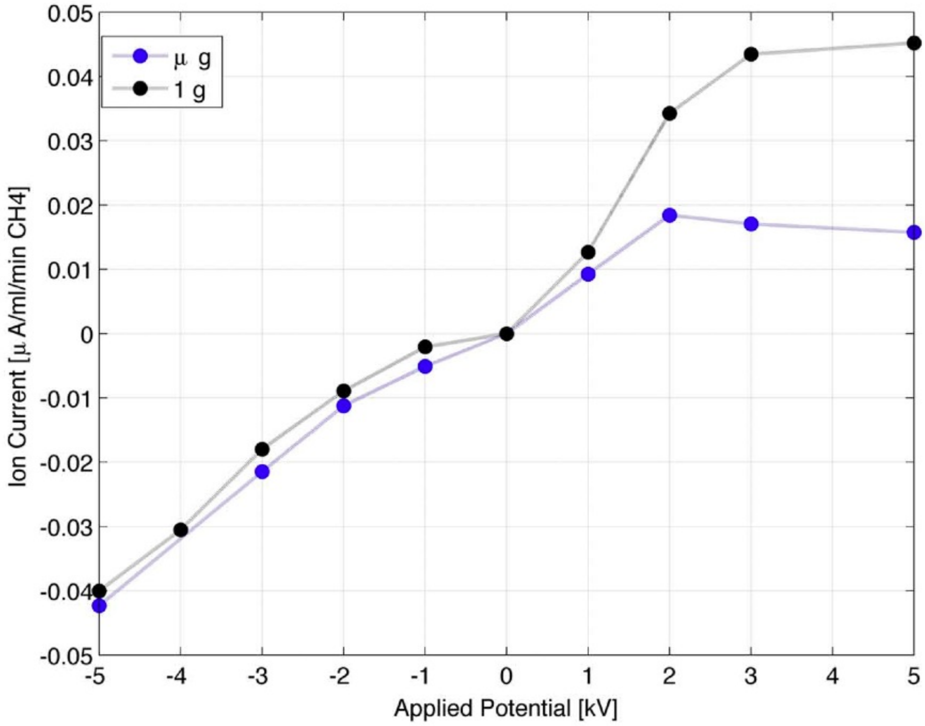


Figure 3: Ion current as a function of voltage at 1g and μg (27 cm/s, 0.05 SLPM)

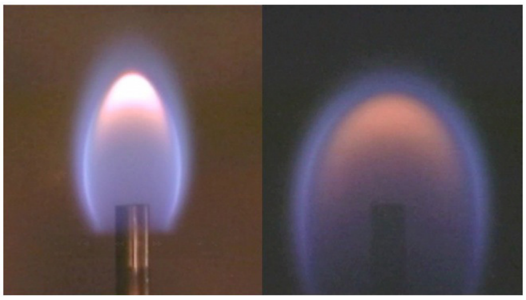


Figure 4: Images of a flame with 3kV mesh voltage applied at 1g and μg

in their research that similar field strengths were necessary to simulate microgravity in an Earth based laboratory environment.

It is possible to use the images to relate approximately the ion driven wind velocity with the buoyancy driven velocity. Computing the flame's area in order to determine current density at the flame surface, and computing the increase in velocity resulting from work on the flame (e.g. gravitational or electrical), we have,

$$v_{elec} = \left(\frac{2jx}{\rho k}\right)^{\frac{1}{2}} \tag{1}$$

$$v_g = \left(\frac{2\vec{g}x(\rho - \rho_{hot})}{\rho_{hot}}\right)^{\frac{1}{2}} \tag{2}$$

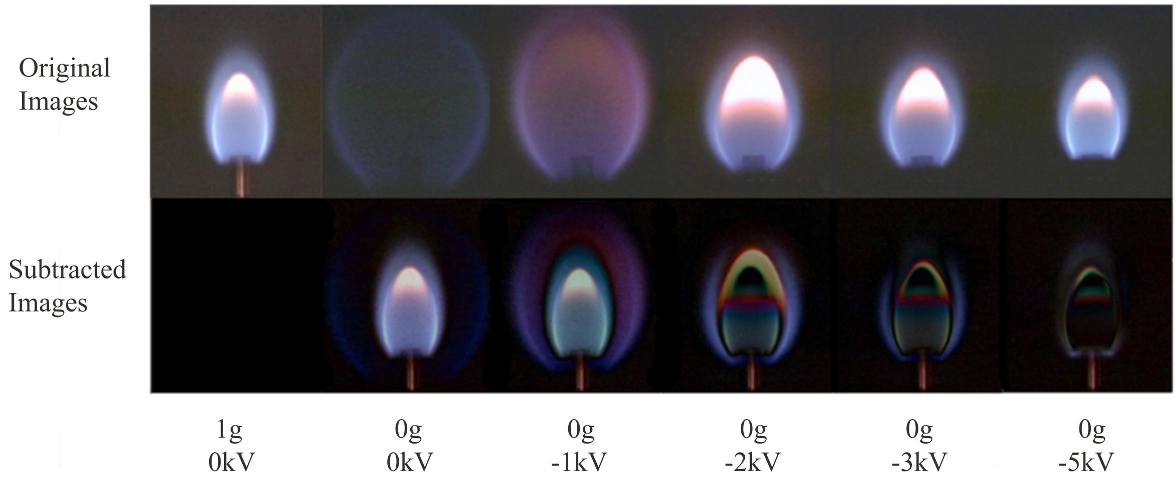


Figure 5: Intensity difference between μg flames with an electric field and a 1g flame

where j is the average current density $[A/m^2]$, ρ is gas density, and k is the ion mobility of H_3O^+, which is generally accepted as a dominant ion in hydrocarbon combustion [Pedersen and Brown, 1993]. The change in mobility and density with temperature produces a negligible change in their product and is not evaluated. Assuming both are acting over the same distance, the buoyancy driven velocity is 95% of the electric field driven velocity using the measured ion current. This is a very promising comparison, but variations in flame area can alter the result by changing the current density. Therefore, it is important to develop a consistent measure of the flame boundary. Such refinements are part of our ongoing research.

Variable	Value
ρ	1.2 kg/m^3
ρ_{hot}	(1/7)*ρ_{air}
I	2.2 μA @ -5kV
A	1 cm^2 @ -5kV
k	$2.9 \times 10^{-4}\ \ m^2/V \cdot s$ [Papac, 2005]

5 Conclusions

When applied to a flame, an electric field can induce convection by an ion-driven wind. For the flame conditions studied, a 1 kV/cm average electric field strength in microgravity can simulate the effect of an $1g$ body force, which is analogous to results shown by Carleton et al. [1998] in a $1g$ environment. Additional experiments and numerical models will aid in comparing species concentrations and velocity fields in similar environments for detailed comparisons. Testing under varying field strengths will illuminate the extent that buoyancy and the ion-driven wind are related. Further work is needed to refine the measurements as well as quantify the electric field induced velocity. The results would allow for studies at variable simulated gravity levels to help understand how minor changes in a flame's flow field can alter reaction rates. The power consumption of the system, computed from the ion current and applied voltage is 10 mW.

6 Acknowledgements

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7 Disclaimer

Product names and models are provided only for clarification and are in no way an endorsement on the part of NASA or the federal government.

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