

EFFECTS OF ELECTRIC FIELD ON HYDROCARBON-FUELED FLAMES

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INTRODUCTION

It has been observed that flames are susceptible to electric fields that are much weaker than the breakdown field strength of the flame gases.¹⁻⁶ When an external electric field is imposed on a flame, the ions generated in the flame reaction zone drift in the direction of the electric forces exerted on them. The moving ions collide with the neutral species and change the velocity distribution in the affected region. This is often referred to as ionic wind effect. In addition, the removal of ions from the flame reaction zone can alter the chemical reaction pathway of the flame. On the other hand, the presence of space charges carried by moving ions affects the electric field distribution. As a result, the flame often changes its shape, location and color once an external electric field is applied. The interplay between the flame movement and the change of electric field makes it difficult to determine the flame location for a given configuration of electrodes and fuel source. In normal gravity, the buoyancy-induced flow often complicates the problem and hinders detailed study of the interaction between the flame and the electric field.

In this work, the microgravity environment established at the 2.2 Second Drop Tower at the NASA Glenn Research Center is utilized to effectively remove the buoyant acceleration. The interaction between the flame and the electric field is studied in a one-dimensional domain. A specially designed electrode makes flame current measurements possible; thus, the mobility of ions, ion density, and ionic wind effect can be evaluated.

EXPERIMENTS

Figure 1 shows the test section of the experiment apparatus. Fuel gas is issued from a porous brass spherical burner with a diameter of 12.7 mm, which also serves as the inner electrode. A 1.6 mm OD stainless steel tube provides fuel passage and electric connection to the burner. It is insulated with a 2.3 mm ID thin-wall ceramic tube, which prevents any electric current from leaking to the surrounding gases. The outer electrode is a Buckyball-shaped Faraday cage with an inner diameter of 70 mm.⁷ The two electrodes are arranged concentrically to establish spherical equipotential surfaces in between, except the local region of the thin stainless fuel tube where the electric field deviates from spherical symmetry. The outer electrode is made of a nylon wire frame coated with a thin layer of copper. A group of wire members at the top of the Buckyball that covers a solid angle of 1.6 Sr is electrically separated from the rest of the ball so that the current through this part can be measured independently. An adjustable high-voltage DC source provides desired voltages and polarity between the two electrodes. The fuel system consists of a fuel bottle, a pressure regulator, a mass flow meter and a solenoid valve to provide constant fuel flow during the drop. During a test run, the flame is ignited at normal gravity. As soon as the ignition is confirmed, the drop rig is released and the high-voltage is turned on. The current value is logged by an onboard computer and the flame images are acquired with a CCD camera. The output signal of the camera is sent to a ground device via a fiber-optic cable for recording. Three types of fuels were tested: ethylene, methane and propane. The applied voltage covered two ranges: from -0.6 kV to -2.0 kV and from +0.8 kV to +2.0 kV with a 0.2 kV increment between two neighboring test points. Flames with no applied voltage were also tested for comparison. A fixed fuel flow rate for each fuel was selected for adequate

flame size. Since flames of the three different fuels behave similarly, only the test results with ethylene fuel at a flow rate of 2.3 mg/s burning in the atmospheric pressure will be discussed below.

RESULTS AND DISCUSSIONS

Figure 2 shows flame images of sixteen tests, acquired 1.8 seconds into free fall. The magnitude and polarity of the applied voltage marked on each image represent the voltage of the outer electrode vs. that of the inner electrode. For most cases, the top portion of the flame is quite spherical. For negative applied voltages, as the magnitude of the voltage increases, the flame size decreases monotonically, while the intensity of the flame increases. The blue color of the flames indicates low or no soot inside the flame. For positive applied voltages, the size of the flame slightly decreases as the voltage increases. The flames are much dimmer than the negative voltage cases. Various intensities of the orange/red color in the flame seem to indicate that the soot content decreases at low positive voltages and then increases at high positive voltages. Figure 3 shows the average flame radius as a function of time. With zero applied voltage, the flame radius increases during the entire course of 2.2 second free fall. For +2.0 kV applied voltage, the flame radius also increases during the drop, but at a lower rate than the zero voltage case. The flame radius of the -2.0 kV case essentially remains constant. The observed flame behavior suggests that the flame reaches a quasi-steady state quicker in the presence of an electric field.

The current magnitude averaged over elapsed time from 1.6 seconds through 1.8 seconds vs. applied voltage for 14 tests is plotted in Fig. 4. The magnitude of the current increases with the magnitude of the applied voltage as expected, i.e., the increased voltage strips more ions from the reaction zone. The relationship between the voltage and current does not follow Ohm's law because the conduction of electricity through gases is fundamentally different from that through metals. In gases, the conduction of electricity is carried out by moving ions, thus the net charge density must not be zero. As a result, the current density is proportional to the electric field multiplied by the divergence of the electric field. Therefore, the relation between the current and the field becomes nonlinear. In addition, the flame radius varies with applied voltage. The location of the flame, as the source of ions, also affects the current.

It is known that the flame reaction zone of the present tests is thin in comparison with the distance between the two electrodes and the apparent resistivity in it is low because of the co-existence of positive and negative ions. Thus, the voltage drop across the two electrodes mostly takes place in the two electrode spaces, (i.e., the spaces between the flame and electrodes). In each electrode space, the charge carrier is unipolar. There is neither charge generation, nor charge recombination in an electrode space. By integrating Gauss's theorem of electrostatics and the equation of conservation of electric charges, an equation relating the total voltage, total current, the mobilities in the two electrode spaces, and the flame radius can be obtained.⁷ Applying the resulting equation to the experimental data, we obtain (a) for negative applied voltages, the mobilities are 45.9 cm²/s/v and 2.2 cm²/s/v for negative and positive ions, respectively, and (b) for positive applied voltages, the mobilities are 0.44 cm²/s/v and 10.3 cm²/s/v for negative and positive ions, respectively. It is noticed that in either case the mobility of negative ions is much lower than that of electrons (the mobility of electrons is more than 1000 cm²/s/v),^{8,9} indicating that electrons are captured by neutral species soon after leaving the flame reaction zone. The distribution of the charge density, $\sigma(r)$, for the two cases of +2.0 kV and -2.0 kV was evaluated and plotted in Fig. 5, based on the obtained mobility data. It can be seen that the charge density is very low compared with the gas density (e.g., at standard conditions, there

are 2.69×10^{19} molecules per cubic centimeter). Therefore, only a very small amount of ions are removed from the flame gas.

To evaluate the impact of the moving ions on the velocity distribution of gases, the Navier-Stokes equations must be invoked, in which the effect of the electric field is represented by a body force term. In a one-dimensional spherically symmetric case, this body force is proportional to the total current and inversely proportional to the ion mobility, i.e., $f = I/(4\pi Kr^2)$.⁷ By defining a variable, $F(r)$, such that $dF/dr = -f$, $F(r)$ can then be lumped into the pressure gradient term in the momentum equation⁷ and viewed as an apparent

$$\text{pressure: } F(r) = \frac{I}{4\pi} \left(\frac{1}{K_o r_o} - \frac{1}{Kr} \right).$$

Figure 6 shows the distribution of the apparent pressure, $F(r)$, based on the data obtained from the +2.0 kV case and the -2.0 kV case. Note that the electric field-induced body force is always in the same direction as that of the moving ions, thus it is inward (i.e., compressive) in the inner electrode space and outward (i.e., expansive) in the outer electrode space. As a result, the field-induced pressure becomes positive in the inner electrode space and negative in the outer electrode space. For a one-dimensional case, the conservation of mass relates a change of the velocity distribution to a change of the density distribution. Since the apparent pressure, $F(r)$, is about six orders of magnitude lower than the ambient pressure in which the drop tests were conducted, the density change caused by the apparent pressure is negligible and so is the velocity change. Therefore, the ionic wind effect is negligible in the current test conditions.

CONCLUSIONS

The electric current through a spherical flame region has been measured successfully using the present experiment apparatus. The current data were used to estimate the mobilities of ions in electrode spaces. The values of the mobilities suggest that soon after leaving the flame reaction region, the electrons attach themselves to neutral molecules or radicals. The ion number densities in electrode spaces are also calculated, indicating very low ion concentration in the gases. The ionic wind effect in a spherically symmetric system can be studied as an apparent pressure term and is found to be negligible. Many flames do not reach quasi-steady state during the drop test so that longer microgravity time is needed.

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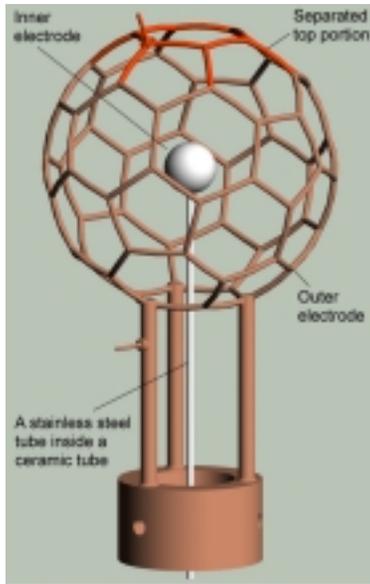


Figure 1. The test section of the experiment apparatus. The red top portion of the outer electrode is electrically separated from the rest of the electrode.

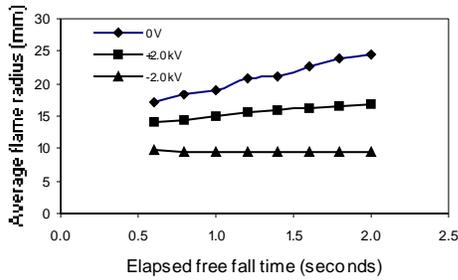


Figure 3. The flame radius vs. time. For both zero and +2.0kV cases, the flame radius increases with time, but more rapidly in the zero voltage case. For the -2.0 kV case, the flame radius is significantly smaller than the zero voltage case and essentially remains unchanged.

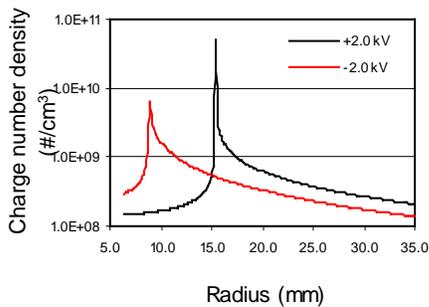


Figure 5. Distribution of charge number density for two tests, assuming each ion carries a single electric charge only. The peak of each curve is located at the flame radius.

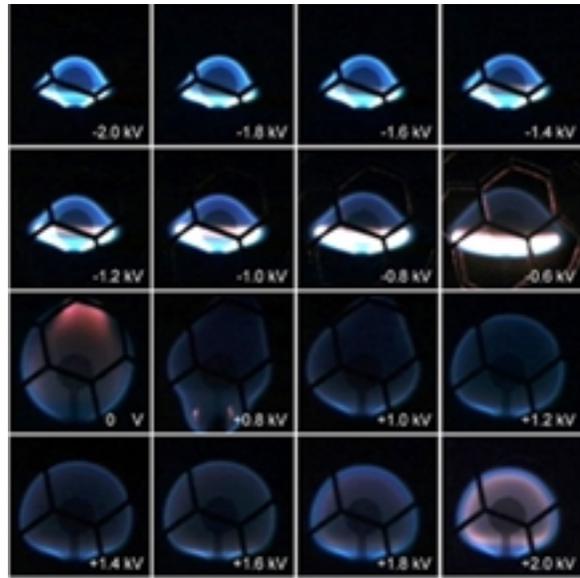


Figure 2. Ethylene/air diffusion flames in sixteen drop tests. The dark lines in each image are out-of-focus elements of the Buckyball. For most cases, the top portion of the flame is quite spherical.

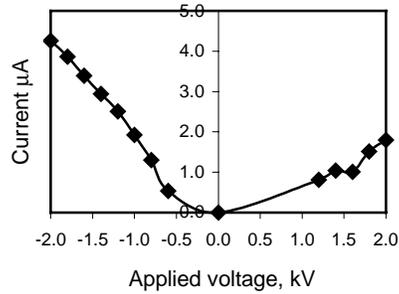


Figure 4. Absolute value of current vs. applied voltage. The current value of each test in the plot is averaged between 1.6 seconds to 1.8 seconds in free fall.

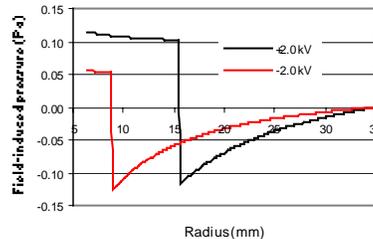


Figure 6. Distribution of the apparent pressure for two tests. The apparent pressure is always compressive (positive) in the inner electrode space and expansive (negative) in the outer electrode space because of different directions of the electric force in the two regions. The field-induced pressure is negligible in comparison with the atmospheric pressure for the current test conditions.