SPHERICAL ETHYLENE/AIR DIFFUSION FLAMES SUBJECT TO CONCENTRIC DC ELECTRIC FIELD IN MICROGRAVITY†

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INTRODUCTION

It is well known that microgravity conditions, by eliminating buoyant flow, enable many combustion phenomena to be observed that are not possible to observe at normal gravity. One example is the spherical diffusion flame surrounding a porous spherical burner [1,2]. The present paper demonstrates that by superimposing a spherical electrical field on such a flame, the flame remains spherical so that we can study the interaction between the electric field and flame in a one-dimensional fashion. Flames are susceptible to electric fields that are much weaker than the breakdown field of the flame gases [3-7] owing to the presence of ions generated in the high temperature flame reaction zone. These ions and the electric current of the moving ions, in turn, significantly change the distribution of the electric field [8]. Thus, to understand the interplay between the electric field and the flame is challenging. Numerous experimental studies of the effect of electric fields on flames have been reported [9-15]. Unfortunately, they were all involved in complex geometries of both the flow field and the electric field, which hinders detailed study of the phenomena. In a one-dimensional domain, however, the electric field, the flow field, the thermal field and the chemical species field are all co-linear. Thus the problem is greatly simplified and becomes more tractable.

EXPERIMENTAL METHODS

Experiments with ethylene diffusion flames burning in air at atmospheric pressure subjected to under various voltages were conducted in the 2.2-second drop tower at NASA Glenn Research Center [16]. The fuel system on the drop rig includes a stainless steel fuel bottle, a pressure regulator, a metering valve, a solenoid valve and a spherical burner, which is a brass porous sphere, 12.7 mm in diameter. By adjusting the pressure regulator and the metering valve, the fuel system can provide the desired constant fuel flow rate during the drop test. Figure 1 shows the test section of the experiment, which consists of a pair of concentric spherical electrodes. The inner electrode utilizes the spherical burner, while the outer electrode is a spherical Faraday cage having a 63.5 mm ID, made of copper wires. A floating, adjustable, high DC-voltage source provides the desired voltage and polarity between the two electrodes, generating an electric field in the radial direction. By adjusting the applied voltage, the strength of the electric field can be controlled. The burner is connected to the fuel supply system using thin stainless-steel tubing having a 0.9 mm ID. To accommodate the fuel supply tube, the bottom part of the outer electrode has a 13 mm diameter opening where the copper wires turn to a direction parallel to the fuel tubing. The schematic drawing in Fig. 1 illustrates the relation between the flame and the electric field. During a test, the flame was ignited at normal gravity using a hot-wire igniter, which was

† The relevant NRA project is "Effects of Electric Field on Soot Processes in Non-buoyant Hydrocarbon-fueled Flames."

then retracted outside the outer electrode to avoid interfering with the flame and the electric field. Following ignition, the drop rig was released and the high DC-voltage turned on. The flame images were acquired at a rate of 30 frames per second using a CCD color camera on board the drop rig. The video signal from the camera was transmitted, via a fiber-optic cable system, to a computer on the ground, where the signal was digitized and stored in the hard drive of the computer for later analysis. A large number of drop tests were conducted with various fuel flow rates and applied voltages. Spherical flames and strong effects of the electric field on the flames were observed. The results of the tests are described in the next section.

RESULTS AND DISCUSSION

A series of screening tests with various ethylene flow rates were carried out in the absence of the electric field to establish a baseline flame commensurate with the above-mentioned electrode dimensions. The results of those tests show that a flame having a 2.5 mg/s ethylene fuel flow rate can serve as a proper baseline flame. It was observed that in about 0.2 seconds after the start of free fall, the flame changed from a teardrop shape typical of normal gravity conditions to a spherical shape typical of microgravity conditions. The flame radius increased slowly during the drop, similar to flames studied by other workers [2,17]. Due to the limited microgravity time, it is not clear if a quasi-steady state was reached. Figure 2a shows the flame image acquired at 1.6 seconds into free fall. The flame appears to be a blue sphere, about 38 mm in diameter, surrounding an orange-colored soot-containing region.

Flame images with three different applied voltages for each polarity are shown in Figures 2b-g. The electric voltages and polarities marked on each image represent those of the outer electrode with respect to the inner electrode. It can be seen that the upper portion of all these flames is quite spherical, especially when positive voltages are applied. However, the bottom portion of these flames deviates from a spherical shape due to the non-spherical distribution of the electric field. All these flame images were acquired at 1.8 seconds after the start of free fall. Figures 2b,d and f show the flame under positive 1.0, 1.5 and 2.0 kV, respectively. In these cases, the radius of the upper portion of the flame becomes slightly smaller than the zero-voltage flame (Fig. 2a). The flame becomes increasingly dimmer because the soot containing zone inside the flame diminishes with increasing voltages. Figures 2c, e and g show the corresponding flame images with negative applied voltages of 1.0, 1.5 and 2.0 kV, respectively. When the applied negative voltage increases, the radius of the upper portion of the flame decreases significantly, while the brightness of the flame increases. The flame becomes purely blue when the applied voltage is –1.5 and –2.0 kV. The observed flame shape change is likely due to the electric-field-induced body force, i.e. ionic wind effect [7]. The flame reaction zone is very thin in comparison with the distance between the flame and either electrode. The ions generated in the flame reaction zone are partially, or totally, removed from the flame by the electric force, depending on the amplitude of the applied voltage. The positive ions move toward the negative electrode, while the negative charge carriers, either electrons or negative ions, move toward the positive electrode. It is generally believed that in the flame reaction region, the negative charge carriers are mostly electrons [4-6]. After leaving the flame, electrons tend to attach to the molecules of either cold air or fuel gas, forming negative ions. Note that on each side of the flame, there is only one type of charge carrier, either positive or negative. When the ions move toward the electrodes, they collide with neutral molecules, resulting a body force from a macroscopic point of view. The additional gas movement caused by this body force is often referred to as ionic wind. In the present configuration, the electric-field-induced body forces on the two sides of the flame are directed in opposite directions. The integrated results of the body force over the entire distance between the two electrodes should be responsible for the changes of the flame shape. The observed disappearance of soot is consistent with early experiments reported by other workers: Weinberg and co-workers [10,18,19] noticed that the electric field caused significant reductions of carbon deposition in their opposed-jet flame experiments; Saito et al. [12] observed similar reduced soot emissions when an electric field was applied in their jet diffusion flame experiments. In the present experiments, although the soot-containing zone diminishes with both electric polarities, the mechanisms seem to be different. When the outer electrode is negative the flame is relatively intense with modest heat losses and a relatively short residence time for the fuel in soot forming regions of the flame; the short residence time inhibits the formation of soot precursors and soot leading to a blue flame. In contrast, when the outer electrode is positive the rate of combustion per unit of flame surface is smaller; then radiation should be important and the lower flame temperatures reduce rates of soot precursor and soot formation even though residence times of fuel in potentially soot-forming regions are longer.

A system is presently under development to measure the electric current passing through the spherical portion of the flame, which will provide information on the distribution of the electric field. Subsequently, tests with different hydrocarbon fuels (i.e. propane, methane, etc) will be conducted to evaluate fuel effects.

ACKNOWLEDGMENTS

This work is supported by the Microgravity Research Division of the NASA Office of Life and Microgravity Science and Application. The authors greatly appreciate assistance of Eric D. Baumann and Andrew J. Jenkins in drop tests. Matthew Ellis, an intern with NASA Glenn, assisted with drop testing in the 2.2 Second Drop Tower.

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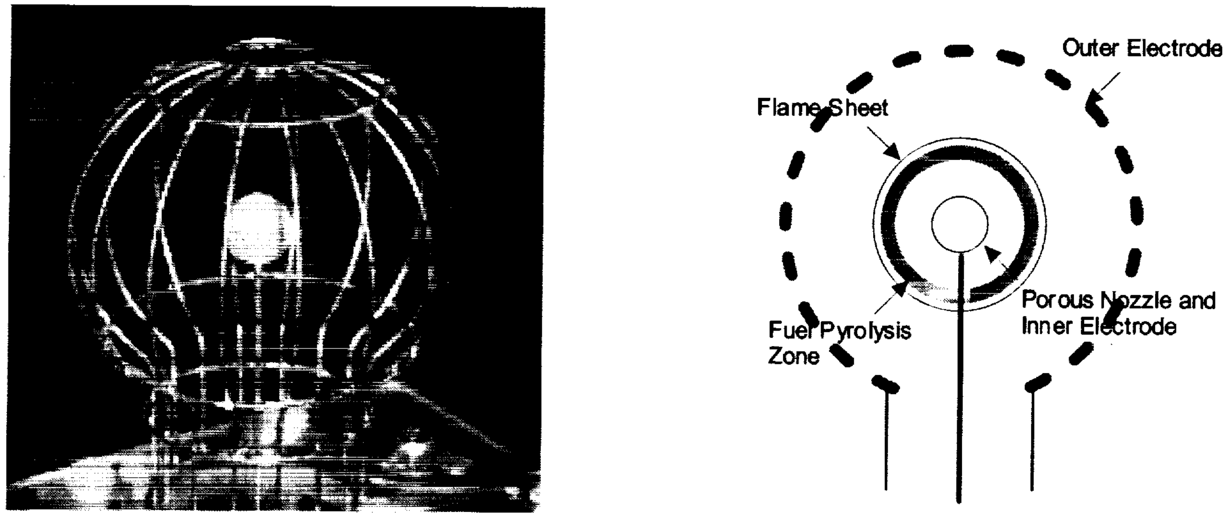

Figure 1. On the left is a photograph of the test section used to conduct the drop tests shown in Fig. 2. The OD of the porous spherical nozzle is 12.7 mm, while the ID of the outer electrode is 63.5 mm. On the right is a sketch illustrating the relationship between the flame and the two electrodes.

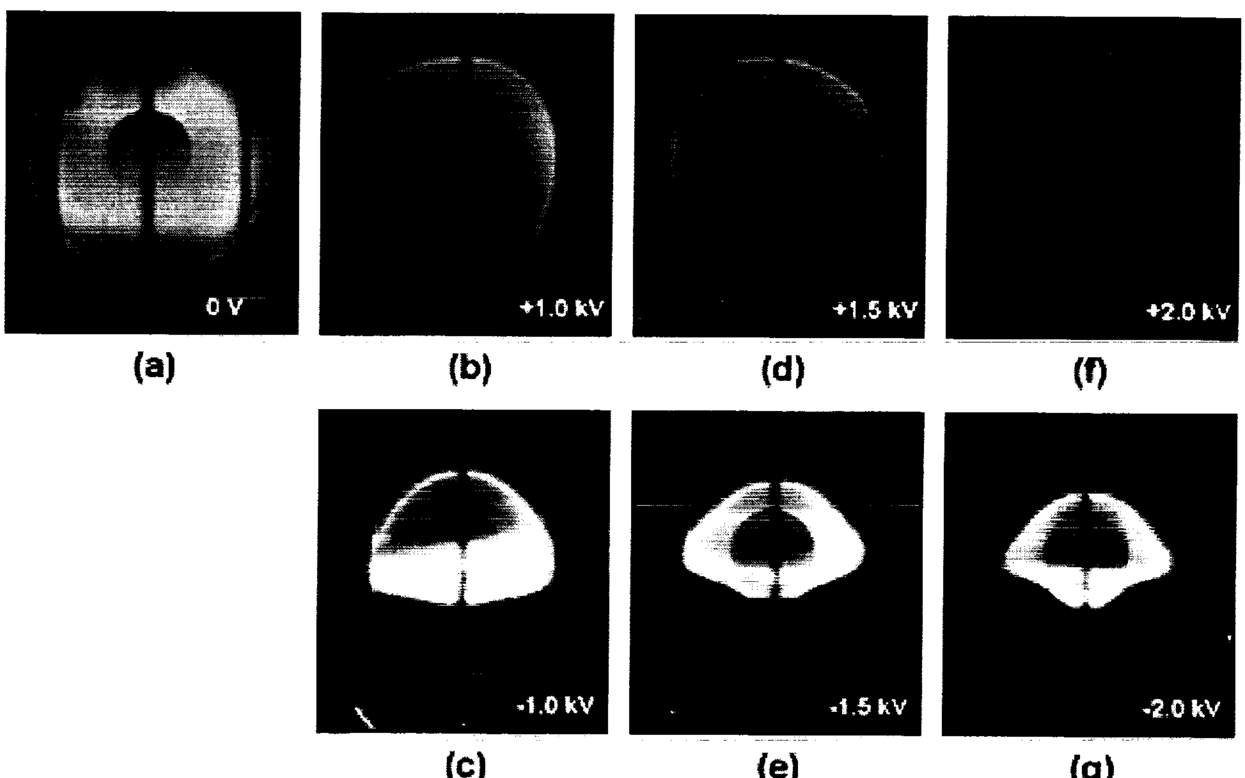

Figure 2. Images of non-buoyant ethylene diffusion flames from a porous spherical burner, subject to various DC voltages. The voltages marked on images are those of the outer electrode with respect to the inner electrode, i.e. the inner electrode is assumed to be at zero volts. The vertical dark lines are the out-of-focus elements of the Faraday cage. The darker center portion in the images is the porous spherical burner, which also is the inner electrode.