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THE EFFECTS OF BUOYANCY AND DILUTION ON THE STRUCTURE AND LIFT-OFF OF COFLOW LAMINAR DIFFUSION FLAMES

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Introduction

The ability to predict the coupled effects of complex transport phenomena with detailed chemical kinetics in diffusion flames is critical in the modeling of turbulent reacting flows and in understanding the processes by which soot formation and radiative transfer take place. In addition, an understanding of those factors that affect flame extinction in diffusion flames is critical in the suppression of fires and in improving engine efficiency. A goal of this work is to bring to microgravity flame studies the detailed experimental and numerical tools that have been used to study ground-based systems. This will lead to a more detailed understanding of the interaction of convection, diffusion and chemistry in a nonbuoyant environment.

To better understand these phenomena, experimental and computational studies of a coflow laminar diffusion flame have been carried out [1,2]. To date, these studies have focused on a single set of flow conditions, in which a nitrogen-diluted methane fuel stream (65% methane by volume) was surrounded by an air coflow, with exit velocities matched at 35 cm/s. Of particular interest is the change in flame shape due to the absence of buoyant forces, as well as the amount of diluent in the fuel stream and the coflow velocity. As a sensitive marker of changes in the flame shape, the number densities of excited-state CH ($A^2\Delta$, denoted CH*), and excited-state OH ($A^2\Sigma$, denoted OH*) are measured. CH* and OH* number densities are deconvoluted from line-of-sight chemiluminescence measurements made on the NASA KC-135 reduced-gravity aircraft. Measured signal levels are calibrated, post-flight, with Rayleigh scattering. In extending the study to microgravity conditions, improvements to the computational model have been made and new calculations performed for a range of gravity conditions. In addition, modifications to the experimental approach were required as a consequence of the constraints imposed by existing microgravity facilities. Results from the computations and experiments are presented in the following sections.

Computational Approach

The computational model used to compute the temperature field, velocities, and species concentrations, solves the full set of elliptic two-dimensional governing equations for mass, momentum, species, and energy conservation on a two-dimensional mesh [3]. The resulting nonlinear equations are then solved on an IBM RS/6000 Model 590 computer by a combination of time integration and Newton's method. Initial computations employed GRI Mech 2.11 as the chemical mechanism [4].

In order to determine the flame structure under microgravity conditions, the results of a computed solution at normal gravity were used as a starting point. In subsequent calculations, the value of the gravitational acceleration (g) was reduced by 10 cm/sec^2 and a new solution calculated using Newton's method. Initial computations performed with different values for the gravitational constant indicate that buoyancy plays an important role in both the size and shape of the coflow laminar diffusion flame. Figure 1 shows the temperature isotherms for flames computed with $g = 982.0$ and 0.0 cm/sec^2. It is clear from the figure that, as the gravitational constant is lowered, the flames tend to become shorter and broader in appearance.

While large variations in g are important in illustrating the differences between normal gravity and microgravity flame structure, small variations in g are important in determining whether the flame will be amenable for study in the NASA KC-135 or the Lewis drop towers. During the microgravity portion of the KC-135 parabolic trajectory, the value of the gravitational constant can vary by as much as ±1% of Earth's gravity. If the computed structure of the diffusion flame varies significantly under such conditions, then drop tower experiments would be the preferred experimental venue. Numerical studies done prior to the experiments indicated that the flame structure should be insensitive to such fluctuations for this coflowing geometry.

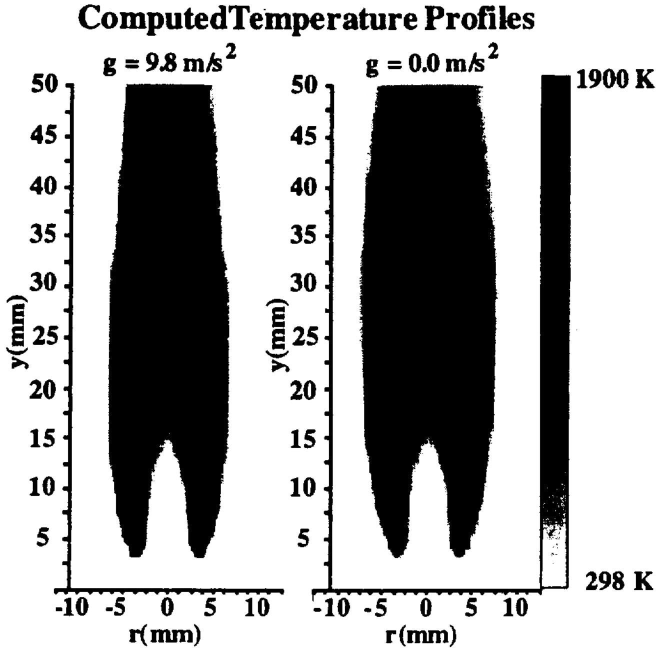

Figure 1. Normal and microgravity temperature profiles computed with GRI Mech 2.11

Experimental System

The burner used in this experiment contains a central fuel jet (4 mm diameter) surrounded by coflowing air (50 mm diameter). The standard flow conditions, which have been measured and modeled extensively in normal gravity, consist of fuel composed of 65% methane diluted with 35% nitrogen by volume to reduce soot (denoted 65/35 in later discussion). The plug flow exit velocity of both fuel and coflow was 35 cm/s. These conditions produce a blue flame roughly 3 cm in length with a lift-off height of 5.5 mm in normal gravity. A wide range of flow conditions were examined in this study, with the fuel composition varied from 100% methane to a 50/50 methane/nitrogen mixture while all velocities were held fixed at 35 cm/s. The same fuel flow conditions were examined with the air coflow velocity reduced to 17.5 cm/s.

Several modifications to the laboratory-based experimental setup were required to make measurements on the KC-135. The burner and ignition system were housed inside a windowed pressure vessel to maintain standard atmospheric pressure. Spectrally-filtered, quantitative chemiluminescence images were collected with a f/4.5 UV camera lens and focused onto a cooled, unintensified CCD camera (Photometrics CH350). The camera/lens system was placed 50 cm away from the flame to ensure a wide depth of field. A color video camera (Sony XC-999) was used to give qualitative insight into flame structure and soot production, as well as monitor the stability of the flame in real time. The computer-controlled exhaust system kept the pressure inside the combustion vessel constant to better than 1%, resulting in a stable flame over a wide range of flow conditions. Although the gravitational acceleration produced by the KC-135 during low-g maneuvers is subject to both positive and negative unsteady forces (g-jitter), the flame remained stable enough for careful emission measurements of both CH* and OH*. During each low gravity maneuver on the KC-135, the combustion vessel pressure and airplane accelerometer signal were recorded simultaneously with the flame emission signal. All Rayleigh calibration was performed, post-flight, on the same optical setup. Details of this procedure are available in earlier work [2].

Data Processing and Quenching Calculations

Emission measurements are integrated through the collection optics along the line of sight. Appropriate background images, taken for both CH* and OH* with the flame extinguished, are subtracted from the raw emission signal. Given that our flame is axisymmetric and that the imaging optics are configured so that the magnification changes by only 1% over the flame width, we can recover a two-dimensional, in-plane intensity distribution proportional to number density with the use of an algorithm that is equivalent to a two-point Abel deconvolution [5]. After inversion, pixel volumes were determined to be cubes of side length 68 μm for both OH* and CH*. Both signals are appropriately corrected to reflect the difference in collection efficiency between the spectrally broad emission signal and the narrow laser line. The collisional quenching rate was calculated for both CH* and OH*, utilizing quenching rate constants from recent literature [6] and major species and temperature profiles computed previously in this flame [1] at standard flow conditions in normal gravity. Note that these quenching values are currently used for all flow conditions. Both CH* and OH* are present in spatially narrow regions of constant temperature (1900 K) and constant quenching. These calculations and corrections resulted in a measured peak mole fraction of 2×10^{-9} for CH* and 1.3×10^{-8} for OH* at standard flow conditions in normal gravity.

Results and Discussion

Figure 2 shows the measured CH* profiles in normal gravity and microgravity over a range of flow conditions. Even in normal gravity, the flame shape, as indicated by the spatial distributions of the CH* radicals, can change significantly as the diluent concentration and coflow velocity are varied. For the three flames in the upper part of Fig. 2, the fuel and coflow velocities are matched at 35 cm/s. This minimizes radial convection, and leads to a higher liftoff height than the two cases shown at the bottom of Fig. 2, which have a coflow velocity of 17.5 cm/s. Liftoff height is also increased as the level of nitrogen dilution is increased. In the normal gravity, matched velocity case, a 50/50 mixture results in a flame lifted off the burner face by over 10 mm.

From the figure we can see that in general, the microgravity flame is shorter, wider, and anchors closer to the burner surface relative its normal gravity counterpart. Since methane is lighter than air, density effects provide a normal gravity flame with a higher lift-off. This difference in lift-off is greatest for the 50/50 CH_4/N_2 mixture with 35 cm/s coflow, where buoyant forces have a long time to operate before ignition occurs. Additionally, the differences in flame front curvature between normal and microgravity are greater in the reduced coflow cases. Note that under some flow conditions seen here, soot luminescence is visible at the flame tip within the CH* detection bandpass. The soot luminescence is greater under microgravity conditions than at normal gravity, and for the reduced coflow case, appears even at a 65/35 CH_4/N_2 ratio.

The computational predictions of microgravity flames becoming shorter and broader were observed in our chemiluminescence measurements. However, preliminary results indicate that the computational model under-predicts differences in flame shape and lift-off height between normal gravity and microgravity. The computed flame shape at standard flow conditions, as measured by the ground-state CH distribution, does not change significantly when the influence of gravity is removed. Given that CH and CH* have been observed and computed to be at the same spatial location in this flame [2], the measured and computed changes in flame shape are not consistent. Microgravity computations of CH* and OH* distributions over a range of flow conditions are planned to better understand these discrepancies and the role of buoyancy in determining flame shape in general.

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Measured CH* Mole Fraction

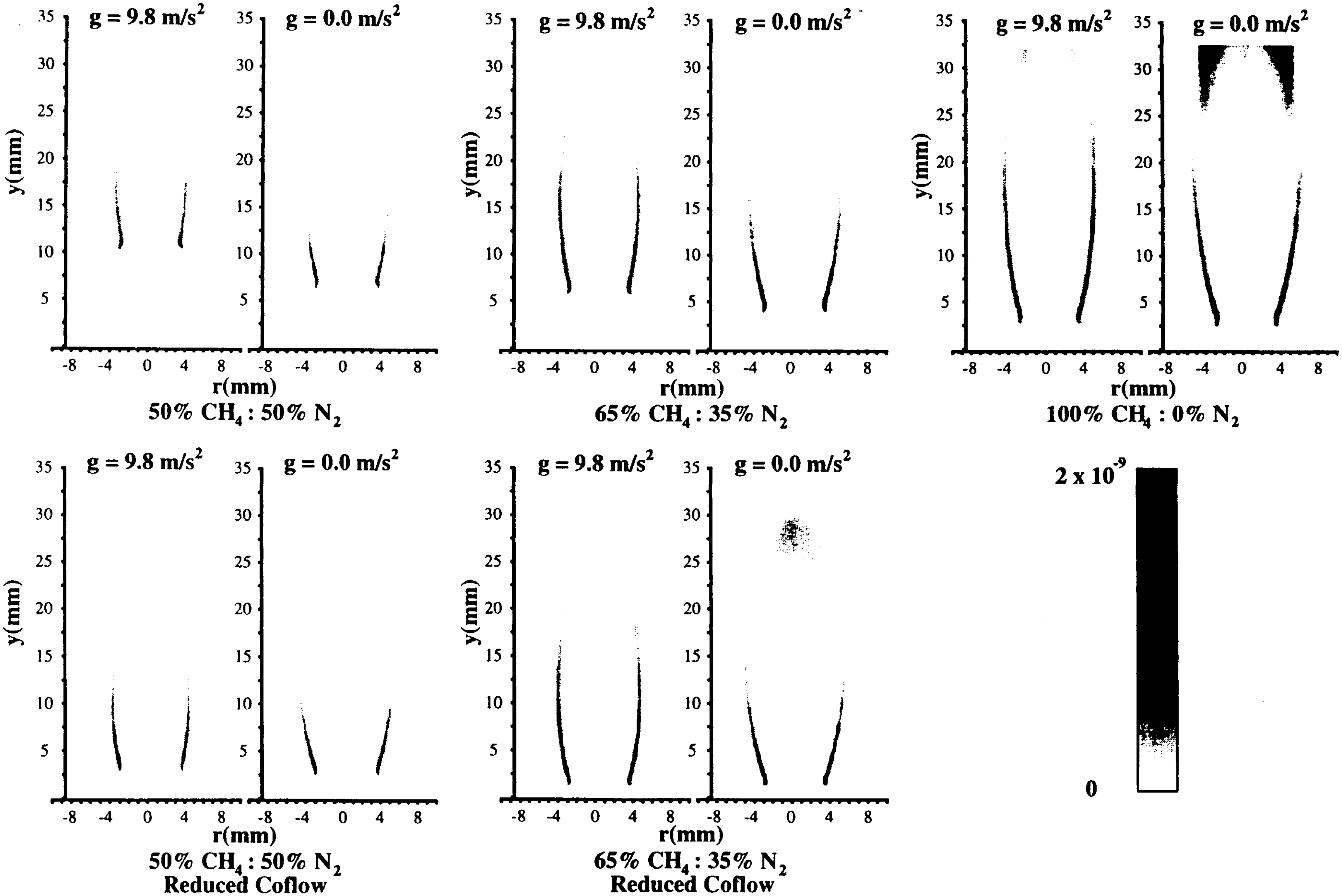

Figure 2.