GRAVITATIONAL INFLUENCES ON FLAME PROPAGATION THROUGH NON-UNIFORM, PREMIXED GAS SYSTEMS

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INTRODUCTION

Flame propagation through non-uniformly premixed (or layered) gases has importance both in useful combustion systems and in unintentional fires. As summarized recently [1] and in previous Microgravity Workshop papers [2-4], *non-uniform* premixed gas combustion receives scant attention compared to the more usual limiting cases of diffusion or *uniformly* premixed flames, especially regarding the role gravity plays. This paper summarizes our recent findings on gravitational effects on layered combustion along a floor, in which the fuel concentration gradient exists normal to the direction of flame spread. In an effort to understand the mechanism by which the flames spread faster in microgravity (and much faster, in laboratory coordinates, than the laminar burning velocity for uniform mixtures)[1], we have begun making pressure measurements across the spreading flame front that are described here. Earlier researchers, testing in 1g, claimed that hydrostatic pressure differences could account for the rapid spread rates [5]. Additionally, we present the development of a new apparatus to study flame spread in free (i.e., far from walls), non-homogeneous fuel layers formed in a flow tunnel behind an airfoil that has been tested in normal gravity.

EXPERIMENTAL APPARATUS FOR FLOOR LAYER STUDIES

The experimental rig, described more fully in earlier papers [1-4], consists of a porous bronze fuel holder 76 cm long by 10 cm wide by 3.2 mm deep, inside a thermally controlled tray that is covered by a stainless steel lid and Lexan gallery. The gallery has a 10 cm square cross section, and for the tests reported here had a closed top and ignition end, while the end opposite the igniter was open. The lid over the fuel holder retracts automatically, and after a predetermined time for fuel vapor to diffuse and form a stratified, flammable boundary layer along the floor, a flame is ignited at one end and spreads to the opposite end of the gallery. We use the same rig for the microgravity experiments in the NASA Glenn 2.2s Drop Tower, with ignition and flame spread after release. Two Cohu model 2200 color cameras image the flame spread from the top and side, each covering half of the gallery, which allows position vs. time data to be obtained.

As mentioned above, in an effort to understand the effects of gravity on the flow field, a microphone was added to the experiment drop rig to measure pressure before, during, and after flame ignition and spread. The microphone is a Brüel & Kjær model 4136 microphone (with a model 2670 preamplifier), installed 36 cm from the igniter and 1.7 cm above the fuel frit, with the microphone face parallel to the gallery side wall. The microphone face extends 0.7 cm from the sidewall. A laptop computer with a National Instruments model AI-16-E data acquisition card collected and recorded the microphone signals at 1000 Hz. The data acquisition software also activated a light emitting diode (LED) in the camera field of view at the start of data collection, allowing for correlation of the pressure and flame location data.

NUMERICAL MODEL FOR FLOOR LAYER STUDIES

The model used in this work was originally developed for studying flame spread across sub-flash liquids, primarily 1-propanol and 1-butanol [6]. The numerical model uses the SIMPLE algorithm [7] and a hybrid-differencing scheme to solve the gas-phase continuity, species, energy, x-y momentum equations and the liquid phase energy and x-y momentum equations. To simulate the experiments, the model initially runs for a specified time period (e.g. 60 seconds) without introducing the ignition source. During this period, a time step of 5 ms is used. This allows the fuel to vaporize at the pool surface and diffuse into the gas phase, setting up initial conditions consistent with the experiments. The output from the non-reacting case becomes an input to the reacting case. Reference [8] contains a diagram and further description of the model, and changes we made to the code are detailed in [4].

NEW APPARATUS AND MODEL FOR FREE LAYERS

A major new initiative in this project has been the development of an apparatus to study flame spread through non-uniform free layers. By free layers, we mean those far from the influence of walls, which can impose heat and momentum loss to the flow field and flame. The details of the apparatus and model are given in [9,10]; here only a summary is given. To obtain a free layer of vaporized liquid fuel in air, the fuel is allowed to flow into a porous airfoil-shaped fuel dispenser in a slow convective flow inside a flow duct (Fig. 1). The fuel evaporates due to heating of the airfoil and forms a non-uniform flammable mixture in the laminar wake of the airfoil that extends the length of the flow duct. The convective flows of interest here are in the range of 10-40 cm/s, and the fuel used for the tests was ethanol. A side view video camera images the flame after it is ignited by a hot wire igniter.

RESULTS

Figure 2 shows the flame velocity as a function of diffusion time, as determined from the video record for 1-propanol at 27 °C, 31 °C, and 35 ˚C in both normal and microgravity. Also shown on the graph are the results for the numerical model. Both the model and the experiment show that the flame spreads faster in microgravity, with increasing initial temperature, and, to a slight degree, with increasing diffusion time (i.e., layer thickness). Of these, the gravitational influence is the most notable. See [1] for a discussion of possible reasons. That the model and the experiment do not agree quantitatively stems from the use of single step kinetics; no one set could be found that agreed at all temperatures.

In Figures 3 and 4 we present side view images of the flames in 1g and μg, respectively. Modeling results of reaction rate contours are also shown for the 1g flame in Fig. 3. The images and numerical computations reveal a double flame structure in 1g, with a premixed upper branch and a lower diffusion flame along the surface consisting of excess air that is unreacted after passing through the lean premixed flame and fuel vapor that evaporates from the surface. There appears to be a hint of a third branch near the surface that is quenched. The initial lean limit height is also labeled (note that the flame exceeds that height once it is spreading), and the flame height, H_f [1]. A representative μg flame is shown in Figure 4. Due to the rig design, we cannot image completely to the surface, so it is not possible to determine if there is a diffusion flame or not. The premixed flame, however, shows a much higher flame height for the same initial conditions. This increased height provides more flame surface area for burning and likely contributes to the flame spreading faster in μg.

To determine if the flame spread and shape are affected by hydrostatic pressure, we began pressure measurements as described above. Figure 5 presents the pressure measured by the microphone as a function of time for flame spread with a 20 second diffusion time, 35 °C initial temperature, in normal gravity. The red line in the figure indicates the time of flame ignition in the video record, and the green line indicates the time when the flame passed the microphone position in the video record. The microphone detects the ignition transients, which decay after time, and then shows the flame passing the microphone, apparently without a change in the pressure response. There is a sinusoidal change in the pressure toward the end of the test, in this case almost 0.4 seconds after ignition. The pressure rose approximately 4 Pa above the background level, fell to 4 Pa below the background level, and then returned to the background reading. As Figure 5 shows, the microphone responds to ignition, but does not appear to respond to the flame front as it passes the microphone. The sinusoidal peak already described may arise from the flame reaching the end of the gallery. These experiments do not show the pressure response of the flame passing a microphone seen in [5]. One reason may be that the gallery walls in the current experiment have rubber strips along the bottom to prevent the escape of fuel vapor. These strips may not contain the pressure pulse from the propagating flame front. Future tests will determine the pressure profile in the flame spread experiments.

A free layer flame obtained with the new apparatus is shown in Fig.6. In this case, ethanol was used as the fuel and the opposed airflow velocity was 25 cm/s. The experiment is described more fully in [9,10]. The flame exhibits a triple like structure, with two branches on either side of the centerline, and a dim trailing flame. We did not measure the fuel concentration in this flow, so we are unable to say with certainty the conditions, but based on the cold flow modeling and measured fuel flow rate, the conditions should be on the lean side of stoichiometric. Thus, it is not a classic triple flame that spans rich to lean conditions. There is an ongoing effort as part of this project to make fuel concentration measurements [11]. The measured flame spread rate for this flame was 148 cm/s, not accounting for the 25 cm/s opposed free stream flow.

CONCLUSIONS

Tests reported here and in earlier papers conclusively show an affect of gravity on flame spread in nonuniform mixtures, with the flames spreading faster in the absence of gravity. The flame height is also higher in microgravity, consistent with faster flame spread. To test the hypothesis that pressure may be a factor, we began making pressure measurements across the flame front. Tests to date are inconclusive. A new apparatus for studying these flames away from the effect of walls has been developed and initial tests show the same high spread rates as for floor layers.

ACKNOWLEDGEMENTS

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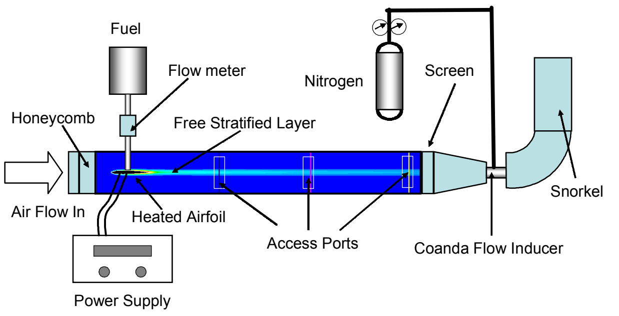

Figure 1. New apparatus for creating free layers of fuel/air mixtures.

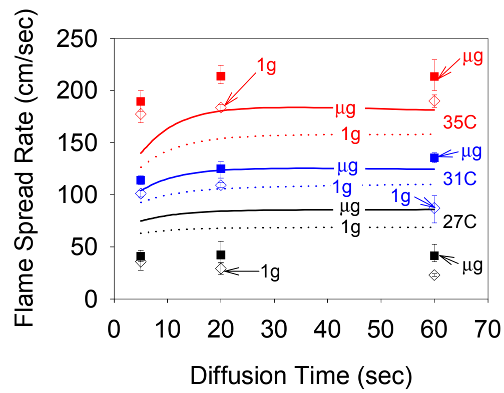

Figure 2 Flame spread rate vs. diffusion time for 1-propanol. Solid line is the model result.

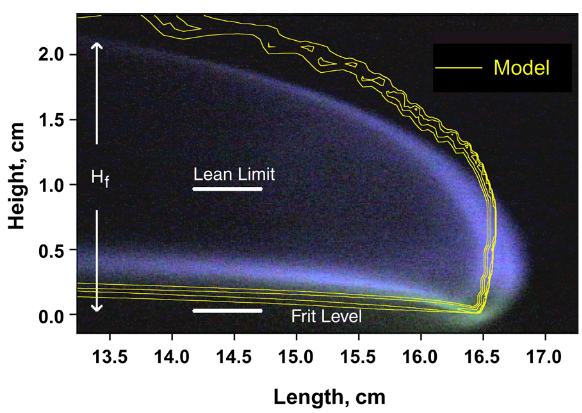

Figure 3. Side view of a 1g flame over 1-propanol at 27 °C in initially quiescent conditions.

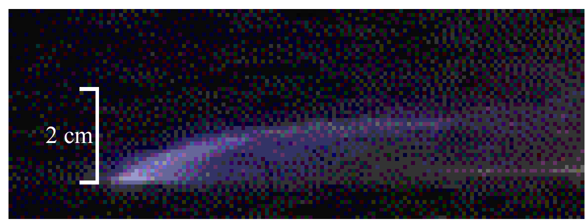

Figure 4. Side view of a μg flame over 1-propanol at 27 °C. The bottom 2 cm of the flame are cropped by the side wall. Total flame height is approximately 3 cm.

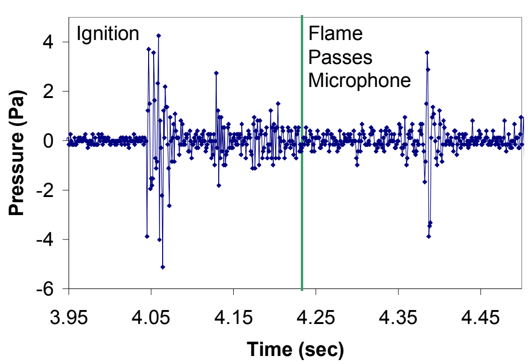

Figure 5 Pressure vs. time for flame spread over 1-propanol at 35 °C.

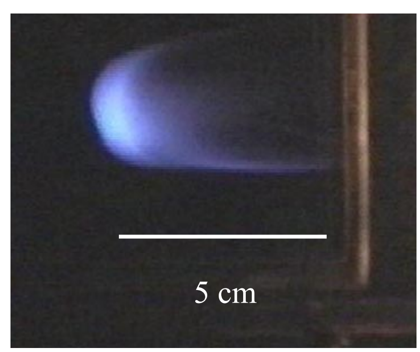

Figure 6 Side view of free layer ethanol flame.