Droplet Combustion in a Slow Convective Flow

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INRODUCTION

The objective of the present flight experiment definition study is to investigate the effects of slow forced convective flows on the dynamics of isolated single droplet combustion and is designed to complement the quiescent, microgravity droplet combustion experiments (DCE-1 and DCE-2) of Williams and Dryer. The fuels selected for this study are the same as those of DCE, namely, a sooting alkane fuel (heptane) and a non-sooting alcohol (methanol), and imposed flow rates are chosen between 0 and 20 cm/s with varying ambient oxygen concentrations and pressures. Within this velocity range, both accelerating and decelerating flow effects will also be investigated. Two different approaches to generate the forced flow are currently under development in ground-based facilities; the first is a flow tunnel concept where the forced flow is imposed against a stationary droplet, and in the second a tethered droplet is translated at a specified velocity in a quiescent ambient medium. Depending upon the engineering feasibility a selection will be made between these two approaches so that the experiment can be accommodated in the Multiple Droplet Combustion Apparatus (MDCA) currently being designed for the International Space Station.

Recently, we have finished designing and fabricating the experimental rigs using both the above mentioned concepts. The flow tunnel concept is implemented in a 2.2 second drop tower rig. Preliminary experiments have been carried out using heptane and methanol in air at atmospheric pressure. The translating droplet apparatus is scheduled to be tested in the 5 second drop facility in the near future. This report presents some of the experimental results obtained for heptane.

EXPERIMENTS

Experiments were conducted in the NASA 2.2 second drop tower using the flow tunnel apparatus. The flow tunnel is capable of producing uniform forced flow velocities in the range of 0 to 20 cm/s within a cylindrical combustion chamber of cross sectional area 314 cm^2 and height 100 cm. Gas flow through the chamber is established by actuating a solenoid valve to open the gas line from a pressurized gas bottle to the chamber. A pressure regulator, located upstream of a sonic orifice, is used to control flow velocities inside the chamber. A specially designed droplet combustion insert was built to be accommodated within this flow tunnel. The insert consisted of 100 micron quartz fiber with a 200 micron bead at its tip, a stepper-motor-driven fuel syringe with a hypodermic needle to deposit the fuel droplet on the bead, and a solenoid-controlled hot-wire igniter. The time-synchronized operations of the flow tunnel, the fuel syringe motor, and the igniter are controlled by a programmable on-board microprocessor. The flow uniformity was checked with the insert in place using a hot-wire anemometer and was found to vary no more than ± 0.5 cm/s at a flow rate of 10 cm/s. Prior to each test the flow field was allowed to reach steady conditions (a period of about 10 s), followed by the formation of a droplet of desired size on the support-fiber bead and then the experimental package was dropped. Ignition was achieved during the free fall in low gravity. During the drop back-lighted images of the droplet, also showing portions of the flame, were obtained using a color CCD camera at 30 frames per second. The back-lighting intensity was adjusted such that the soot-shells formed are visible in the droplet image. A flame camera with a larger field of view captured the flame shapes. Also, a wide-band (0.6 to 40 μm) and a narrow-band (5.1-7.5 μm) radiometers recorded the radiant emission from the burning droplet flame.

RESULTS AND DISCUSSIONS

Heptane droplets of initial diameter varying between 0.8 mm and 1.6 mm were burned in a forced flow of air at atmospheric pressure in microgravity. The flow velocities ranged from 2 cm/s to 10 cm/s. Nineteen successful tests were performed in the 2.2 second drop tower, and the results of these experiments are discussed below.

Flame Shapes:

Heptane droplets burning in air in a slow convective flow (2 cm/s $\leq U_\infty \leq$ 10 cm/s) exhibited luminous, orange flames. As the flow velocity was increased from 2 cm/s to 10 cm/s the upstream leading-edge of the flame became dimmer and turned blue showing that the soot formation ceases there due to insufficient residence time. The flame tips downstream were found to be open. From the flame images various parameters can be identified and measured to characterize the flame geometry as shown in Fig. 1a. It should be noted that the downstream "flame length" corresponds to the visible flame length rather than the closed stoichiometric flame position (shown as the dotted curve in Fig. 1a). Dimensional analysis of this problem using a thin-flame approximation and constant thermophysical properties shows three dimensionless groups that are of relevance to the flame geometry, namely, the Reynolds number Re($=U_\infty D/\nu_\infty$), the stoichiometric coefficient S, and the dimensionless burning rate M_c ($\approx k/\nu_\infty$); where k is the burning-rate constant [1]. The dimensionless parameters W/D, and H_2/D then should correlate with these three dimensionless groups. For the present set of experiments S is a constant and M_c varies over a small range. Figures (2b-2c) show the variations of the dimensionless flame width W/D, and the upstream flame standoff distance H_2/D, with Re (varying approximately as ~1/Re) for four different imposed velocities. The two sets of data corresponding to 5 cm/s are for two different initial droplet sizes (1.12 and 1.45 mm). The downstream "flame length" (H_2-H_1)/D cannot be correlated in similar fashion because of the fluctuations of the downstream yellow tip. Therefore we show the dimensional variation of H_1 against D in Fig. 2d. At 4 cm/s pulsation of opening and closing of the flame tip is reflected in the wiggle in Fig. 2d.

Soot-Shell Behavior:

Figure 2 shows a sequence of back-lit images of the droplet, starting shortly after ignition. A partial outline of the flame, the droplet, and the shoot shell are visible. Initially, the soot shell takes a cup-shaped form with the open end facing downstream. Soon after, the perturbations to the temperature and the velocity fields caused by the fiber generate an effective thermophoretic force that draws a portion of the soot volume toward the droplet surface along the fiber. This impinging soot flow is eventually forced away from the droplet surface at a larger distances from the fiber by the Stefan-flow drag, thereby forming a soot ring downstream of the droplet. This behavior is consistent with earlier discussions [2]. As the droplet burns, the soot ring remains trapped behind it, and at the end of the burn the soot ring is deposited on the support fiber. The soot rings were found to form only up to an imposed velocity of 8 cm/s for the range of droplet initial sizes examined in this study. At the highest velocity studied here, 10 cm/s, soot rings were not observed, and all of the soot escapes through the open flame tip downstream, similar to the condition shown in Fig. 2a. The maximum diameter of the soot ring during an experiment decreased with increasing flow velocity. Further studies are needed to address the occurrence and cessation of the soot rings. The planned translating droplet experiments with the fiber support perpendicular to the flow should also provide further insight into the soot-ring formation process.

Burning Rates:
Burning rate constants k, are obtained by fitting a linear curve to the D^2 versus time plots of the experimental data. The burning rates calculated for the quiescent conditions are slightly higher than the free-floated droplet results of DCE, but comparable to the fiber-supported droplet results of FSDC (Williams, this Volume). Figure 3 shows the variation of (k/k_0-1) as function of $Re^{1/2}$. Here k_0 is taken to be 0.75 mm^2/s and the Re is calculated based on the initial droplet diameter with the properties evaluated at the mean temperature (850°K). Also shown in the figure for comparison is a correlation obtained earlier [3], namely, $(k/k_0-1)=0.3\ Re^{1/2}$. Clearly, at higher Re values the well-known $Re^{1/2}$ relationship seems to hold. However, for Re smaller than one the trend is not linear, and more experimental data are needed to develop a firm correlation. The upcoming experiments with the translating droplet device should provide accurate data in this region.

CONCLUDING REMARKS
The current experiments in the ground-based facilities along with the theoretical models that are under development should provide tools for the development of the test matrix for the space experiments. With the limited microgravity time, acceleration/deceleration effects as well as extinction phenomena can not be studied in the ground-based facilities. Future space experiments should help address these issues.

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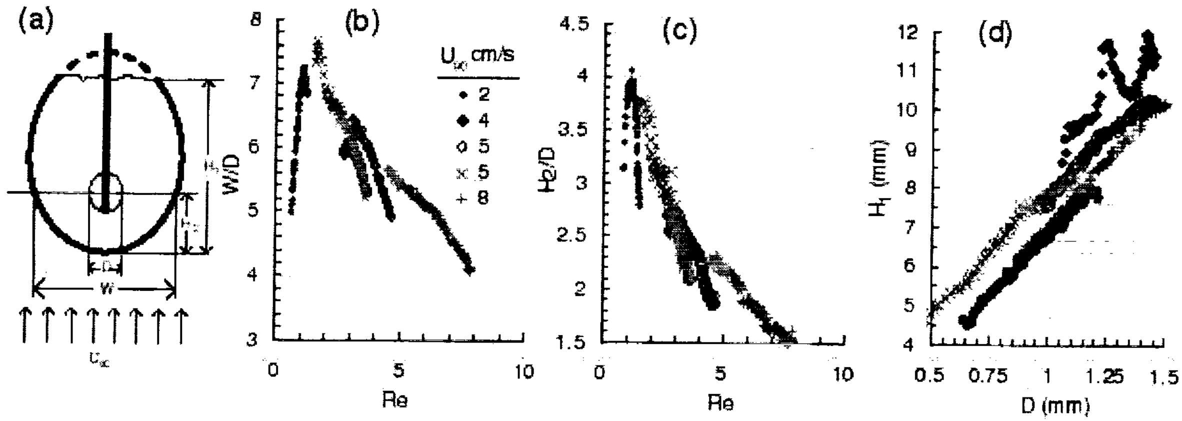

Figure 1. (a) Schematic illustration of the flame; (b) flame width, (c) upstream standoff distance, and (d) flame height variation.

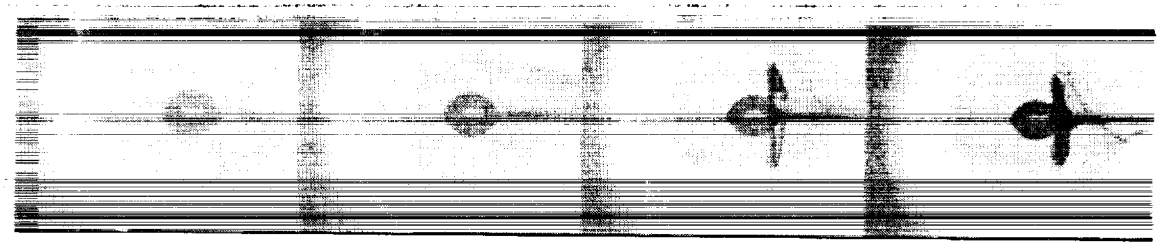

Figure 2. Soot-shell dynamics during n-heptane droplet combustion in air at atmospheric pressure with an imposed flow velocity of 3 cm/s (images are shown at 2/15 second intervals).

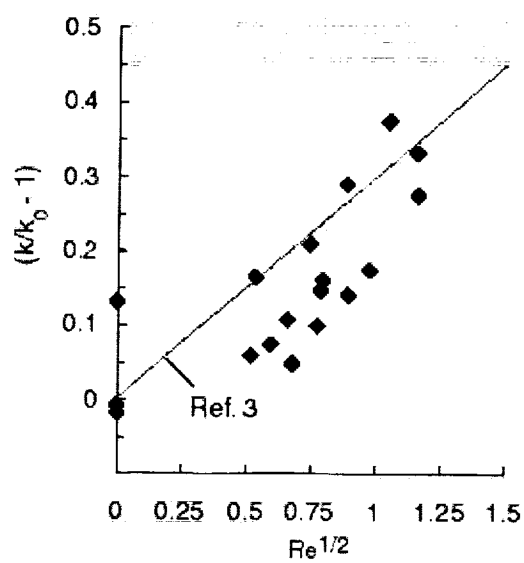

Figure 3. Heptane droplets burning in a forced flow in air at atmospheric pressure under microgravity.