PRELIMINARY ASSESSMENT OF THE BURNING DYNAMICS OF JP8 DROPLETS IN MICROGRAVITY

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ABSTRACT

In this report we present new data for fuel droplet combustion in microgravity to examine the influence of ambient gas and fuel composition on flame structure and sooting dynamics for droplets with initial diameters in the range of 0.4mm to 0.5mm. The fuels are JP8 (a kerosene derivative) and nonane. The ambient gas is air and a mixture of 30% oxygen and 70% helium, the latter having been examined for burning under conditions where soot formation is minimal. Some data at elevated pressures are also reported.

The burning process shows a nonlinear D^2 progression which is independent of soot formation as burning in a helium inert showed the same nonlinear trend. Flames were proportionally farther from the droplet surface in helium than they were in air. A nondimensional parameter is presented that consolidates the three 'standoff' distances for the droplet, flame and soot shell diameters within the initial diameter ranges examined.

INTRODUCTION

In an effort to expand the fuel systems that have been studied in microgravity to a fuel which has direct application to terrestrial energy processes, we explored the feasibility of microgravity for studying the burning behavior of the complex fuel system JP8. JP8 is the primary fuel for military aircraft and ground vehicles, and it also serves as the coolant for aircraft and engine subsystems [Edwards and Maurice 2001; Heneghan et al. 1996]. It does not fit the mold for microgravity droplet combustion experimentation because it is highly multicomponent with constituents that have wide ranging boiling points, heats of vaporization and sooting tendencies. On the other hand a single component fuel like n-nonane (C_9H_{20}) is more typical of those selected for microgravity droplet combustion studies (i.e., alcohols, alkanes, and their mixtures [Shaw and Chen 1997; Lee et al. 1996; Avedisian 1997]). Such an 'ideal' fuel provides a useful basis for comparing with JP8, and nonane has a boiling point in the mid-range of JP8.

The experiments utilize droplets in the initial diameter range of 0.4mm to 0.5mm. The ambient gas was air and a mixture of oxygen and helium. The latter was included in order to compare burning of the same fuel under conditions where soot formation would be significantly reduced. Measurements of droplet, flame and soot shell diameters were made and correlated using a nomdimensional parameter that consolidated the measurements.

EXPERIMENT

Spherical droplet flames were created by burning droplets in a quiescent ambient gas environment within microgravity (created by a drop tower) to eliminate buoyancy induced flows. A fiber-supported arrangement was used and calibrated against a free droplet design in microgravity under identical conditions of ignition and fuel type (i.e., nonane) and it gave very good agreement with D^2 progressions from the fiber supported droplets. An instrumentation package which contains a combustion chamber and two cameras inside a drag shield (one for

16mm color or black and white photography using a LOCAM high speed 16mm film camera, and the other for video imaging) was released into freefall to create microgravity. The droplets were then ignited and their burning histories recorded. Quantitative measurements of droplet, flame and soot shell diameters were obtained by transporting images from the 16mm black and white, and color, movie films to a PC and analyzed using a commercial software package (ImagePro). The backlit droplet images were illuminated using either a 16W halogen bulb ('low intensity' backlighting) or a 150 watt bulb ('high intensity' illumination) with the latter being required for the heavily sooting JP8 compared to nonane in order to provide visibility of the droplet. Care was taken to ensure identical backlighting intensities when comparing different conditions for their influence on soot formation.

The fiber support design [Avedisian and Callahan 2000] consisted of two fine SiC fibers 12microns in diameter and crossed at an angle of 120°. By using two crossed fibers and mounting the droplet at the junction of the cross, droplets did not slide along the fiber. Ignition was by two sparks of 0.5ms to 0.8ms duration positioned on opposite sides of the droplet (using four electrodes) and activated 320ms after the package was released. Ignition in a helium inert using our spark ignition system required that the oxygen concentration be increased to 30% (70% He) for the same parameters of ignition energy and duration as in air.

DISCUSSION

Figure 1 shows selected color images of a JP8 droplet burning in microgravity at their peak image intensities. Combustion in air (1a) shows an intense yellow color while in a helium inert (1b) the yellow zone is reduced significantly with the flame structure showing an outer blue zone and a faintly yellow interior. The reduced luminosity indicates less soot formation in helium, most likely due to a lower flame temperature in helium compared to air. At 3atm (1c) in helium soot formation return dominated the luminosity (the influence of pressure on accelerating soot precursor reactions overrides the lower flame temperature in helium). Figure 2 shows selected backlit black and white images of nonane (a) and JP8 (b) droplets at atmospheric pressure. The JP8 droplet is completely obscured in Figure 2b while the nonane droplet and soot shell are still clearly visible in Figure 2a indicating much less soot formation for nonane relative to JP8. Figure 3 shows the evolution of droplet diameter for JP8 in air (3a) and helium (3b). The gap in data for JP8 in air (3a) was caused by the soot shell which became so thick mid-way through burning that the droplet was not visible.

Immediately after ignition, JP8 experienced significant droplet heating as indicated by the relatively constant or increasing droplet diameter (due to swelling) while nonane showed almost no evidence of droplet heating after ignition. This difference is likely due to the lower product of liquid density and specific heat of nonane compared to JP8 [Reid et al. 1987; Coordinating Research Council 1983]. In helium (3b) the JP8 droplet heating period is eliminated, perhaps because of the higher average gas phase thermal conductivity in helium compared to air which would increase gas phase heat transport to the droplet. After the heating period, both nonane and JP8 showed a time dependent burning rate that was evidenced by nonlinear diameter progressions in both air and helium (Figures 3a and 3b). We may then conclude that soot formation is not responsible for nonlinear burning of JP8 because the effect occurred under conditions where soot formation was significantly reduced (i.e., in helium).

The evolution of flame standoff ratio for JP8 in air is compared to JP8 in helium in figure 3c. The flame is proportionally farther from the droplet in helium than in air. There are two influences to consider to explain this trend: helium lowers the flame temperature; and helium weights the average gas thermal conductivity to a higher value. The data show that the JP8 flame position is farther from the droplet in helium compared to that in nitrogen. Therefore, the increased gas thermal conductivity overrides the reduction of flame temperature. Figure 4 shows the evolution of soot shell standoff ratio. It increases with time and tracks with the flame position. The gap in data after ignition ($t/D_o^2 < 0.25mm^2/s$) is caused by the delay period of soot formation where the shell has not yet fully formed.

The three measurements of droplet, flame and soot shell diameters for JP8 and nonane exhibit distinctly different time dependencies as indicated in Figures 3 and 4. We attempted to consolidate these data with a suitable nondimensional parameter. Some guidance for this effort was explored by scaling formulations for the forces acting on soot agglomerates due to Stefan drag, thermophoresis and diffusiophoresis [Jackson et al. 1992; Ben-dor et al. 2003]. One parameter that worked reasonably well was $\frac{D_f - D_s}{D_s - D}$ as a function of scaled time, t/t_b where t_b is the total burning time defined as the time for the flame to disappear. Figure 5 shows the result. The number of data involved in this scaling are determined essentially by the number of movie frames where D_s could be reasonably defined. A power-law relationship of the form $\frac{D_f - D_s}{D_s - D} = C \cdot \left(\frac{t}{t_b}\right)^{-n}$ correlated the measurements with $C \approx 3.47$ and $n \approx 0.43$. The utility of such a correlation for microgravity droplet flames in quiescent conditions is that with knowledge of the droplet and flame position, the soot shell is determined. The correlation appears reasonable for droplets in the diameter range investigated. Using it for droplets outside of the range of initial droplet diameters examined here and for other fuel systems requires further testing.

CONCLUSIONS

The flame structure and influence of ambient gas on combustion of JP8 droplets showed trends similar to those found for a single component fuel except for much more soot formation. The evolution of droplet diameter produced a time dependent burning rate in both helium and air which showed that soot formation was not likely to be responsible for nonlinear burning. The flame was farther from the droplet in helium than that in air, showing the dominance of helium thermal conductivity on increasing the average gas thermal conductivity and heat transfer to the droplet. Extinction of JP8 was not observed for burning in air but was commonly found for burning JP8 in an ambience consisting of 30% oxygen and 70% helium.

The measurements of droplet, soot shell and flame diameter were consolidated onto a single curve using a scaling relationship that will require further investigation for additional fuels and mixtures to establish the generality of the approach. Sooting tendencies were deduced primarily by comparing photographic image intensities. Quantitative methods for measuring soot volume fraction of JP8 and related heavily sooting fuels in microgravity would better establish the influence of parameters on trends of soot formation.

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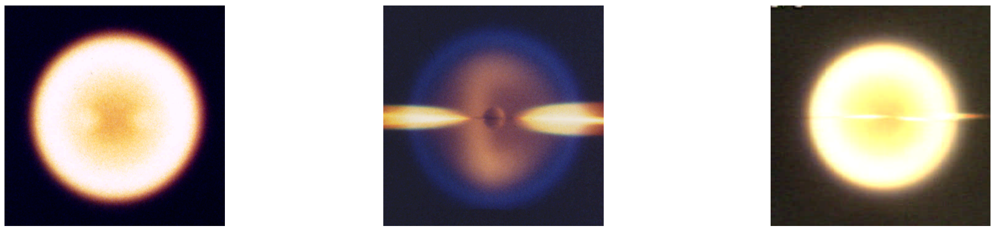
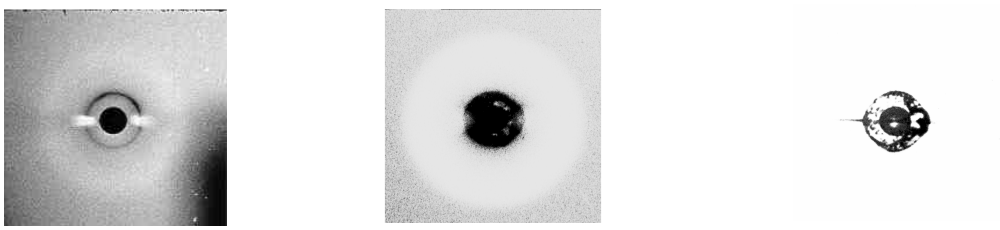


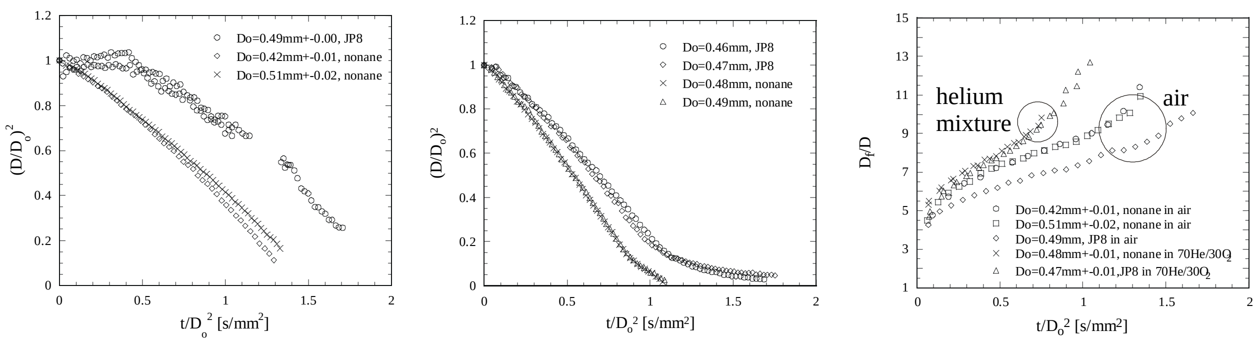
(a) (b) (c)

Figure 1: (a) JP8, 1atm in air; (b) JP8, 1atm in 30% O_2/70% He; (c) JP8, 3atm in 30% O_2/70% He



(a) (b) (c)

Figure 2: (a) nonane, low intensity; (b) JP8, low intensity; (c) JP8, high intensity



(a) (b) (c)

Figure 3: (a) evolution of droplet diameter in air; (b) evolution of droplet diameter in 30% O_2/70% He; (c) flame standoff ratios in air and 30% O_2/70% He

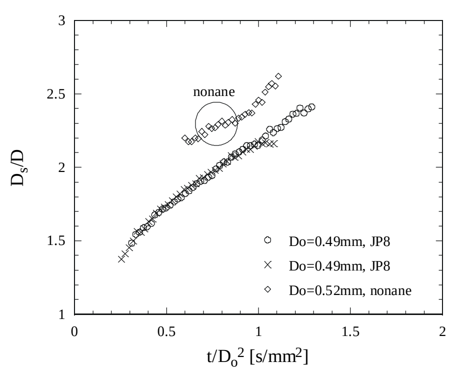


Figure 4: nondimensional soot shell position in air

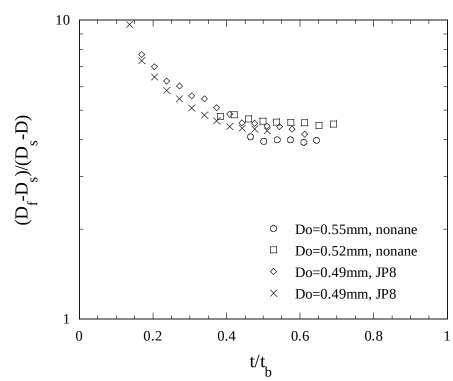


Figure 5: scaling of droplet, flame and soot shell diameters in air