

# ANALYSIS OF MSL-1 MEASUREMENTS OF HEPTANE DROPLET COMBUSTION

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## Introduction

A droplet combustion experiment (DCE) was performed on the MSL-1 mission of the Space Shuttle Columbia. There were two flights of this mission—STS-83 in April of 1997 and STS-94 in July of 1997. The reflight occurred because a fuel-cell power problem onboard the shuttle forced an early termination of the first flight; this was the only shuttle mission to be flown twice. DCE data were obtained during both flights. A fiber-supported droplet combustion (FSDC) experiment also was run on STS-94. This smaller “glovebox” experiment, which investigated the combustion of fiber-supported droplets in Spacelab cabin air, had previously flown on the first United States Microgravity Laboratory (USML-1) mission of STS-73, but successful measurements with heptane as the fuel in this experiment were first obtained on STS-94. Although heptane droplet combustion in convective flow also was studied on STS-94, only data without forced convection are considered here. The objective of the present paper is to analyze the results on heptane droplet combustion in quiescent atmospheres.

## Data Analysis

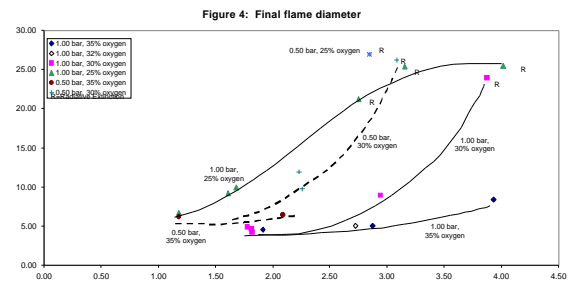
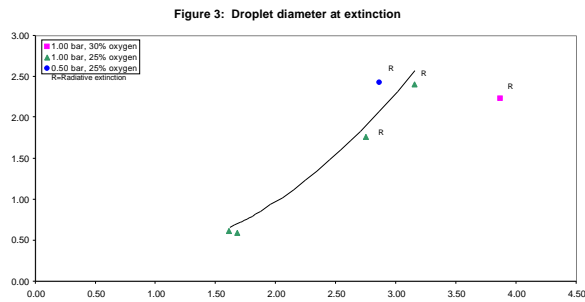
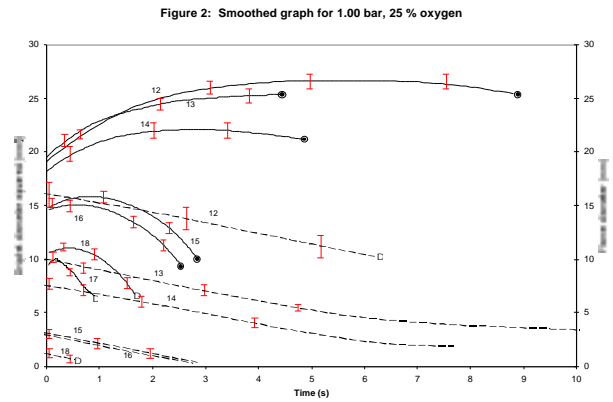
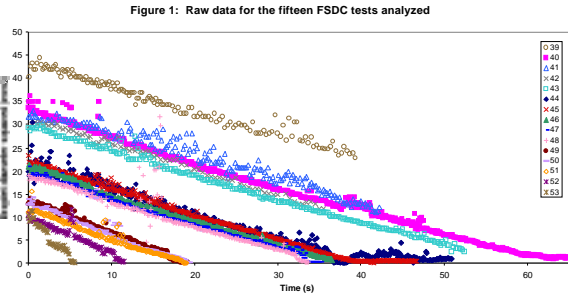
A PC-based image-analysis system [1] was used to measure droplet and flame diameters as functions of time. Reduction of some of the data from STS-83 was reported previously [2]. In the present work, two approaches to reducing flame-diameter and droplet-diameter data were employed. One involved graphically exhibiting raw data extracted from the image-analysis system, and the other involved smoothing with a second-degree Loess smoother [3] in the statistical software package S-Plus. Full details of the data analysis, these reduction techniques and various characteristics of the resulting procedures that dictated selection of the methods adopted will be available elsewhere [4] and can be obtained now by contacting the authors.

## Results

Results are reported in full elsewhere [4]; there were 34 DCE tests in helium-oxygen atmospheres and 4 in air, 2 fiber-supported. Figure 1 shows raw data on droplet diameters for the 15 FSDC tests, while for comparison Fig. 2 shows smoothed data on both droplet and flame diameters for the DCE tests in one particular atmosphere. Here solid curves are for the flames and dashed curves for the droplets, error bars indicate maximum scatter, a large dot signifies flame extinction and D means that the image drifted out of the field of view. Figure 2 clearly shows diffusive extinction for the small droplets and radiative extinction for the larger droplets. Results are discussed first in terms of extinction diameters and next in terms of burning rates.

## Extinction Diameters

When diffusive extinction occurs, droplet diameters at extinction are very small, usually too small to be measured and quite possibly often zero. For seven DCE experiments it was found that diameters at extinction are too small to be measured, that is, less than a limit of resolution between about 0.05 mm and 0.5 mm, depending on the experiment. Only three experiments have measurable droplet extinction diameters for diffusive extinction, two of which are shown in Fig. 3, the third being similar but in a different atmosphere. On the other hand, for radiative extinction, the droplet extinction diameters are much more readily determined. Four such

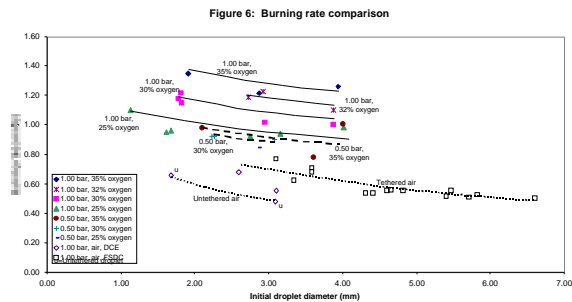
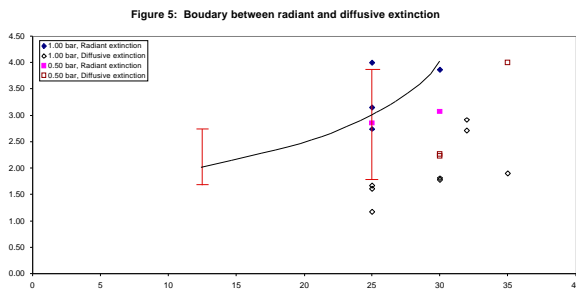


droplet diameters at extinction were obtained and are also plotted in Fig. 3, identified by the symbol R.

From the data in Fig. 3 for 1.00 bar and 25% oxygen, through which the curve is drawn, it is seen that in this atmosphere the droplet extinction diameter increases with increasing initial droplet diameter. This trend is consistent with theoretical estimates for radiative extinction. For diffusive extinction with the flame in the quasisteady region, if the liquid fuel remains pure then the droplet diameter at extinction theoretically is independent of the initial droplet diameter [5]; the available data are insufficient to test this prediction. Although no significant functional dependences for diffusive extinction could be measured, trends were obtained for radiative extinction. The point at 1.00 bar and 30% oxygen in Fig. 3 suggests a decrease in the droplet radiative extinction diameter with increasing oxygen concentration at a given pressure and initial droplet diameter, while that at 0.50 bar and 25% oxygen indicates an increase in the droplet radiative extinction diameter with decreasing pressure at a given oxygen mole fraction and initial droplet diameter. Both of these trends are expected from the dependence of the reaction rate on pressure and oxygen concentration.

In contrast to droplet diameters at extinction, substantial data were acquired on flame diameters at extinction in helium-oxygen atmospheres. Indications are that flames always extinguish at flame diameters large enough to be measured. Since fewer theoretical predictions have been made of these flame extinction diameters (final flame diameters), additional theoretical work is needed for making comparisons with the present experimental results, which are partially plotted in Fig. 4 and discussed elsewhere [4] (because of insufficient space here).

It is of interest to exhibit graphically the boundary between radiative and diffusive extinction, in a plane of oxygen mole fraction and initial droplet diameter for different pressures, as determined by these experiments. Figure 5 is such a plot, with the open symbols corresponding



to observations of diffusive extinction and the closed symbols correspond to radiative extinction. Figure 5 shows that, although there is considerable uncertainty about exactly where the boundary lies, the general direction and curvature of the boundary between the two regimes seems well defined. The error bars indicate the range of uncertainty of the boundary location at 1.00 bar; data are insufficient to distinguish differences in boundary locations at 1.00 bar and 0.50 bar.

### Burning Rates

A summary graph of burning-rate constants as functions of initial droplet diameter is shown as Fig. 6. In this figure the solid curves pertain to helium-oxygen atmospheres at 1.00 bar, the dashed curves to helium-oxygen atmospheres at 0.50 bar and the dotted curves to air. The general trend of a decrease in the burning-rate constant with increasing initial droplet diameter is evident in all of this data. Some specific data points, particularly the triangular points representing 1.00 bar and 25% oxygen and the circles representing 0.50 bar and 35% oxygen, suggest the existence of a minimum burning-rate constant at a particular initial droplet diameter, but in view of the general trends of most of the data, it seems likely that these minima are only apparent and are the result of run-to-run variability, although their existence cannot entirely be ruled out. The decreasing of the burning-rate constant with increasing initial droplet diameter is consistent with previous work [6], where the change was attributed to the formation of larger quantities of soot.

Figure 6 clearly shows that the burning-rate constant decreases with increasing dilution, as expected. It seems noteworthy that the extent of this increase is much greater at 1.00 bar (solid curves) than at 0.50 bar (dashed curves). At 0.50 bar the results for 35% and 30% oxygen are very close together, and even the single point available at this pressure for 25% oxygen is quite close to these. Although there would be greater confidence in the conclusion that the dilution effect is small at 0.50 bar if more data were available at that pressure, there seems to be sufficient data to motivate seeking possible theoretical reasons for the small effect. The results in Fig. 6 for air clearly show the increase in the burning-rate constant caused by the fiber support (tether). The two untethered droplets definitely exhibited lower burning-rate constants, and the FSDC tether appears to increase the burning rate more than the DCE tether, which was made of a different material, suggesting that the enhancement may be associated with heat conduction along the fiber from the flame. The burning-rate constants for air are substantially lower than those for helium-oxygen mixtures because of the high thermal conductivity of helium.

### Conclusions

The tests performed during MSL-1 led to the first documented radiant extinction in n-heptane droplet combustion. Tests performed at 1.00 bar showed that diffusive extinction occurs for droplets smaller than 4.1 mm burning in a 35% oxygen environment with helium as the inert. Diffusive extinction also occurs for droplets under 3.2 mm in a 30% environment and 1.7 mm in

25% oxygen. The 20% oxygen environment was shown to be unable to support the combustion of droplets larger than 0.9 mm in initial diameter. At 1.00 bar radiant extinction was observed for droplets over 3.9 mm in the 30% environment and 2.8 mm in the 25% and 20% environment. No tests at 35% in 1.00 bar exhibited radiant extinction (the largest droplet was 4.1 mm). For the half-bar tests radiant extinction was observed during two tests: 3.1 mm initial droplet diameter in a 30% oxygen environment and 2.9 mm initial droplet diameter in the 25% oxygen environment. The quarter-bar tests showed radiant extinction at 35% oxygen with an initial droplet diameter of 2.6 mm and diffusive extinction at 50% oxygen with an initial droplet diameter of about 1.5 mm. These results can be viewed graphically in Fig. 5 with an approximate radiant extinction limit drawn.

All of the droplets exhibited the classic linear decrease in time of the square of their diameter. This behavior occurred independent of the more complex flame behavior. Flames were generally found to grow and then shrink for tests that underwent diffusive extinction, and grow to a maximum diameter, occasionally shrinking slightly, in cases of radiant extinction. Some exceptions were found to this flame behavior, but all occurred during the 1.00 bar 20% oxygen tests, and they were assumed to result from combustion of the accumulated vapors only. In several environments the curves of the square of the droplet diameter as a function of time exhibited a curvature wherein the burning-rate constant decreased over time. The lower oxygen environments, as well as the lower pressures, did not exhibit this curvature.

Finite final flame diameters were measured in all tests that stayed within the view of the flame-imaging camera. The final flame diameters appear to be dependent on initial droplet diameter, especially in cases of radiative extinction. Additionally, several of these droplets in the richer oxygen environments have immeasurably small to zero final droplet diameters, while in other atmospheres the droplet still exists when the flame extinguishes.

Burning rates vary with initial droplet diameter, pressure and oxygen content. The burning-rate constant decreases with increasing initial droplet diameter. Additionally, the pressure and oxygen percentage have the predicted effect on burning-rate constants—decreasing the pressure or the oxygen mole fraction increases the burning rate. More study of the influences of the initial droplet diameter is desirable because the cause of the decrease is not well understood. Further quantitative study of radiant extinction also needs to be done, as does examination of final droplet and flame diameters with diffusive extinction.

#### **Acknowledgment**

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