# Combustion of Interacting Droplet Arrays in a Microgravity Environment

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## INTRODUCTION

Investigations into droplet interactions date back to Rex et al. [1]. Annamalai and Ryan [2] and Annamalai [3] published extensive reviews of droplet array and cloud combustion studies. In the majority of the reviewed studies, the authors examined the change in the burning rate constant, k, (relative to that of the single droplet) that results from interactions. More recently, Niioka and co-workers [4] have examined ignition and flame propagation along arrays of interacting droplets with the goal of relating these phenomena in this simplified geometry to the more practical spray configuration.

Our work has focussed on droplet interactions under conditions where flame extinction occurs at a finite droplet diameter. In our previous work [5], we reported that in normal gravity, reduced pressure conditions, droplet interactions improved flame stability and extended flammability limits (by inference). In our recent work, we examine droplet interactions under conditions where the flame extinguishes at a finite droplet diameter in microgravity. The microgravity experiments were in the NASA GRC 2.2 and 5.2 second drop towers, and the JAMIC (Japan Microgravity Center) 10 second drop tower. We also present progress on a numerical model of single droplet combustion that is in the process of being extended to model a binary droplet array.

## EXPERIMENTAL HARDWARE AND DATA ANALYSIS

The experiments utilized the classical fiber-supported droplet combustion technique. A 125 or 230 μm (depending on the initial droplet size) fiber with a small bead (approximately 1.5-2.0 times the fiber diameter) supported the droplets. The fuel was n-decane for all of the tests. A small coiled hot-wire, withdrawn immediately after ignition, ignited the droplets.

The data for all of the experiments was from two orthogonally located video cameras. The first camera provided a magnified, backlit view of the droplet to obtain the droplet regression history. The second was an orthogonal view of the flame. For many of the tests, the flame was nearly invisible to the CCD camera. For these tests, we suspended a small 15 μm fiber across the droplet and flame to indicate the presence of the flame. The droplet diameter reported herein is an equivalent size obtained by equating the measured volume or the projected area of the droplet to that of the equivalent sphere or circle, respectively [6].

## EXPERIMENTAL RESULTS

While the effects of buoyancy were minimized in the normal gravity testing, they were not altogether eliminated. Our first attempts to perform the same testing in microgravity involved testing in similar ambient conditions as the normal gravity tests. The initial testing [7] showed that the reduced pressure, air ambients that yield a finite extinction droplet diameter in normal gravity do not produce a finite extinction droplet diameter in microgravity. In fact, at pressures down to near the ignitable limit, the droplets burned to completion (or to a size smaller than the support fiber and bead). Thus in order to observe extinction at finite droplet sizes, we performed the microgravity experiments in reduced oxygen mole fraction, reduced pressure ambients.

Initial tests were in a in a 380 mm Hg, 0.17 oxygen mole fraction ambient. Flame extinction at a finite droplet diameter did not occur for either the single droplets or the binary droplet arrays. Consistent with earlier droplet array studies [8,9] the burning rate of the binary array was lower than that of the single droplet. Additionally, the flame size of the array (measured normal to a line between the two droplets) is much larger (nearly 50 percent) than the flame of the single droplets. Finally, while the droplets in both tests burned to completion, the flame surrounding the binary array was much weaker (the intensity of the flame and the SiC fiber on the CCD camera) than the flame surrounding the single droplet.

The best ambient oxygen concentration for realizing extinction in microgravity was a 0.15 oxygen mole fraction ambient. Depending on the pressure, the flame did extinguish at a finite droplet diameter. Figure 1 shows the burning behavior as a function of time for a single droplet and a binary droplet array in a 380 mm Hg, 0.15 oxygen mole fraction (nitrogen diluted) ambient. Referring first to the single droplet tests, there are several noteworthy features of the burning behavior. First, this ambient condition was not flammable in normal gravity. In fact, droplets of this size could not sustain a flame in normal gravity regardless of the ambient pressure. Second, the burning behavior is non-linear. The burning rate is approximately 0.5 $mm^2/s$ immediately after ignition. It then increases throughout the test, reaching a final value nearly 40 percent higher than the value immediately after ignition.

The single droplet behavior presented in Figure 1 was typical over the range of pressures tested. At ambient pressures below 150 mm Hg, the flame extinguished at a finite droplet diameter for the single droplet tests. The extinction droplet diameter increased with decreasing ambient pressure, and at ambient pressures below 90 mm Hg, the flame extinguished almost immediately after ignition. While the extinction diameter was a strong function of pressure, the average burning rate constant was nearly independent of ambient pressure, consistent with the simplified theory for droplet combustion.

Finally, Figure 1 also presents the flame size and standoff ratio (normalized by the droplet diameter at that instant in time) for this droplet. The flame size initially grew with time. At some point in the middle of the burn, the flame size reached a maximum, remained constant for a time, then decreased with time until extinction. The flame standoff ratio, however increased nearly linearly with time throughout the burn. The flames were soot-free (visually) throughout the test, except for a brief period immediately after ignition for the higher pressure tests. Although not presented here, our testing in the 0.15 oxygen mole fraction ambient also examined droplet diameter effects, and ignition energy effects in addition to the pressure effects.

Figure 1, however, shows that the binary droplet array exhibited very different behavior. The flame surrounding the array extinguished quickly after igniter withdraw. The droplet diameter at flame extinction was approximately 1.1 mm for both droplets. The flame size (measured perpendicular to a line between the droplets), similar to the 0.17 oxygen mole fraction tests, was nearly 50 percent larger than the single droplet. In the binary array test, however, the flame size increased reached a maximum but then extinguished before decreasing. The flame standoff increased continuously and linearly until extinction. The above trends were consistent over a range of inter-droplet spacings and ambient pressures. In the 0.15 oxygen mole fraction ambient, in all cases tested, the flame surrounding the binary array always extinguished at a larger droplet size than the flame surrounding a single droplet.

The results cited above display an opposite trend to the normal gravity test results. That is, interactions diminished flame stability in the microgravity tests, whereas in the normal gravity tests, interactions promoted flame stability. This discrepancy may be in part due to the differing ambient oxygen mole fraction ambients in the two studies. Specifically, the large, weak flames in the microgravity tests were most likely strongly influenced by large radiative (spectral, due to the lack of soot) losses from the flame zone. In fact, we believe that the extinction process was dominated by radiative loss [10].

Figure 2 shows the results of a single droplet and a binary droplet array, only in this case, the ambient was 0.25 oxygen mole fraction, 190 mm Hg and the diluent was helium as opposed to nitrogen. Typically, single droplets burning in helium, have high burning rates and lower flame temperatures because of the high gas-phase thermal conductivity than droplets burning in a nitrogen ambient (the same ambient oxygen mole fraction). The flames also have smaller standoff ratios. The result is flames that extinguish at finite-sized droplet diameters, in regions where radiative losses should be smaller than the flames in Fig. 1. Figure 2 shows that the flame surrounding the single droplet extinguished quickly after ignition. The burning rate constant before flame extinction was quite high, 1.0 $mm^2/s$. The flame standoff ratio was approximately 10, and was much smaller than in the nitrogen diluted tests (e.g. Fig. 1).

Figure 2 shows, in contrast to Fig. 1, that the binary droplet array (L = 4 mm) burned for much longer, and extinguished at a smaller size than the single droplet. The trend is opposite to that displayed in Fig. 1, but in agreement with our previous normal gravity testing [5]. Interestingly, while the binary array had a smaller extinction droplet diameter, it also had a much smaller burning rate. The average burning rate constant was 0.75 $mm^2/s$, approximately 25 percent smaller than the single droplet. The flame size and standoff ratio, measured perpendicular to a line between the two droplets, for the binary array was larger than the flame size and standoff ratio for the single droplet. Also, while not presented in Fig. 2, we should note that the flames surrounding the binary droplet array at inter-droplet spacings of L = 8 and 12 mm (merged flames existed for both spacings) both extinguished at droplet diameters smaller than the single droplet. The extinction behavior at an inter-droplet spacing of 24 mm, however, was nearly identical to that of a single droplet. The flames surrounding the droplets (individual flames surrounded each droplet) extinguished nearly immediately after ignition.

The helium and nitrogen diluents clearly exhibit different extinction behavior for the binary arrays (when compared to the single droplets). We believe the difference is primarily a function of the importance of radiative loss from the flame zone. Specifically, the binary arrays in the nitrogen ambient have very large, weak flames, much larger than the flames surrounding the single droplet. These large flames are dominated by radiative loss, and the increase in flame size from the single droplet to the binary droplet array is enough to cause extinction of the binary droplet array. For a binary droplet array, if the inter-droplet spacing were to approach zero, this would create a single droplet whose size was 30 percent larger than each individual single droplet. This single, larger droplet could be larger than the radiative extinction droplet size.

A similar argument can be made to explain the behavior of the helium-diluted tests. In this case, extinction occurs when the residence time is smaller than the required chemical time. For the binary droplet array, if the inter-droplet spacing were zero, this would again create a larger single droplet. This single droplet would have a larger residence time, and thus would not extinguish.

We are also in the process of developing a numerical model of the single droplet and binary droplet array to quantitatively explain the experimentally observed extinction results. The model is based on an existing model of the candle flame. The model is transient, assumes constant properties and Lewis numbers (although each species can have a different Lewis number), and most importantly, includes radiative loss (purely loss using a Planck mean absorption coefficient). We are currently using the single droplet model to predict and explain some of our single droplet results, and are in the process of modifying the code to model the binary droplet array.

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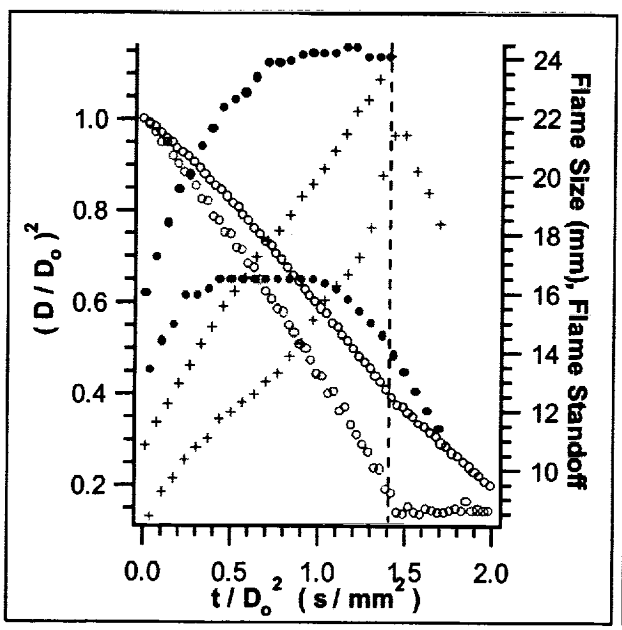


Figure 1. Droplet and flame histories for a Single droplet (red) and a binary array (blue). P = 380 mm Hg, $Y_{O2}$ = 0.17 ($N_2$ diluted).

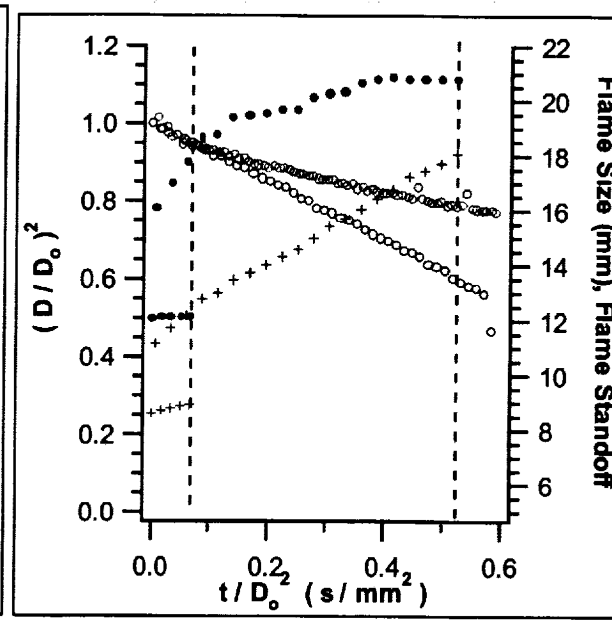


Figure 2. Droplet and flame histories for a single droplet (red) and a binary array (blue). P = 190 mm Hg, $Y_{O2}$ = 0.25 (He diluted).

[for both figures: (o) droplet size; (●) flame size; (+) flame standoff ratio; and the dashed vertical line represents extinction.]