COMBUSTION OF INTERACTING DROPLET ARRAYS IN MICROGRAVITY

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Introduction

Theory and experiments involving single droplet combustion date back to 1953[1], with the first microgravity work appearing in 1956[2]. The problem of a spherical droplet burning in an infinite, quiescent microgravity environment is a classical problem in combustion research with the classical solution appearing in nearly every textbook on combustion. The microgravity environment offered by ground-based facilities such as drop towers and space-based facilities is ideal for studying the problem experimentally. A recent review by Choi and Dryer [3] shows significant advances in droplet combustion have been made by studying the problem experimentally in microgravity and comparing the results to one dimensional theoretical and numerical treatments of the problem.

Studying small numbers of interacting droplets in a well-controlled geometry represents a logical step in extending single droplet investigations to more practical spray configurations. Studies of droplet interactions date back to Rex and co-workers [4], and were recently summarized by Annamalai and Ryan [5]. All previous studies determined the change in the burning rate constant, k, or the flame characteristics as a result of interactions. There exists almost no information on how droplet interactions affect extinction limits, and if the extinction limits change if the array is in the diffusive[6] or the radiative[7] extinction regime.

Thus, this study examined experimentally the effect that droplet interactions have on the extinction process by investigating the simplest array configuration, a binary droplet array. The studies were both in normal gravity, reduced pressure ambients and microgravity facilities. The microgravity facilities were the 2.2 and 5.2 second drop towers at the NASA Glenn Research Center and the 10 second drop tower at the Japan Microgravity Center. The experimental apparatus [8] and the data analysis techniques [9] are discussed in detail elsewhere.

Experimental Results

Extensive testing in normal gravity showed that interaction effects have a stronger influence on the extinction behavior of a binary array than the quasi-steady burning behavior. In normal gravity, k is only a very weak function of the inter-droplet spacing at initial non-dimensional separation distances (L/D) greater than 5. The extinction droplet diameter, D_{ext}, however, is much smaller (if it existed) for the droplet array at an instantaneous L/D of approximately 20. These low pressure, normal gravity environment minimized, but did not altogether eliminate, the effects of buoyancy. Initial drop tower tests [10] 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 the ignitable limit, the droplets burned to completion. Thus in order to observe extinction at finite droplet sizes, we performed the microgravity experiments in reduced oxygen mole fraction, reduced pressure ambients.

The flame did extinguish at a finite droplet diameter at an ambient oxygen mole fraction of 0.15 (depending on the pressure). Figure 1a shows the burning behavior for a single droplet and a binary array $(L \approx 3mm)$ in a 0.15 oxygen mole fraction, $190mmHg$ ambient in microgravity. This oxygen mole fraction ambient condition was not flammable in normal gravity at ambient pressures up to $760mmHg$. The burning behavior is non-linear, with k increasing throughout the flame

lifetime. Finally, this figure shows that the flame size initially grew with time, reached a plateau, then decreased with time until extinction. The flame standoff ratio, however, increased nearly linearly with time throughout the burn.
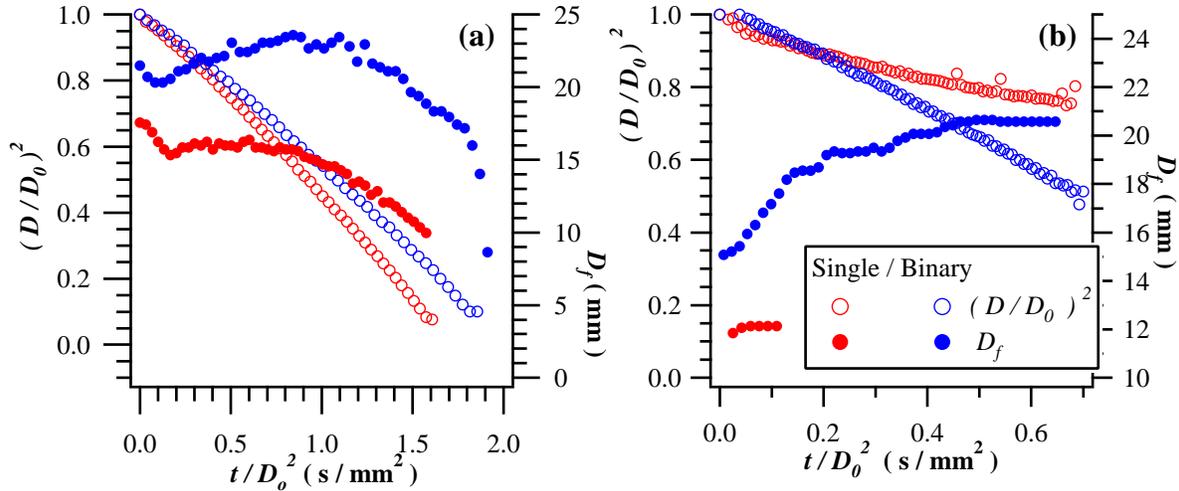

Figure 1: Droplet and flame histories as a function of time for a single droplet and a binary droplet array ($L \approx 4mm$) in (a) 0.15 oxygen mole fraction, $380mmHg$, nitrogen ambient; (b) 0.25 oxygen mole fraction, $190mmHg$, helium ambient in microgravity.

In the 0.15 mole fraction ambient and all pressures ($90 \rightarrow 760mmHg$), the flame surrounding the binary array extinguished at a finite droplet diameter. Figure 1a shows that while the single droplet burned to completion, the flame surrounding the array extinguished approximately one second after the igniter withdrew. The D_{ext} was approximately $1.1mm$ for both droplets of the array. Further, the flame size was nearly 50 percent larger than the flame surrounding the single droplet and the flame was much dimmer. In the binary array test, the flame size increased, reached a maximum, and extinguished. The above trends were consistent over a range of inter-droplet spacings and ambient pressures. In the 0.15 oxygen mole fraction ambient, the flame surrounding the binary array always extinguished at a finite droplet size that was larger than the single droplet extinction diameter.

The results cited above display an opposite trend to the normal gravity test results. That is, interactions diminished flammability in the microgravity tests, whereas in the normal gravity tests, interactions enhanced flammability. The large, weak flames in the microgravity tests were probably more influenced by radiative losses (spectral, due to the lack of soot) from the flame zone than the normal gravity tests.

Recent droplet combustion experiments on the Space Shuttle[11] showed that droplets burning in helium-oxygen ambients exhibited large burning rates, smaller flame standoff ratios and finite-sized extinction droplet diameters. The experiments further demonstrated both modes, diffusive and radiative, of flame extinction. Figure 1b shows the burning history of a single droplet and a binary array in a $190mmHg$, 0.25 oxygen mole fraction (balance helium) ambient in microgravity. The droplet histories were more linear and was much higher for the helium diluted experiments than those in the nitrogen diluted experiments (Fig. 1a). Also, the flames were much brighter in the helium-diluted ambients and the flame sizes and standoff distances in the helium-diluted ambients

were approximately 50 percent smaller. The flame surrounding the single droplet extinguishes quickly after ignition. The flame surrounding the binary array, however, burns much longer, with $D_{ext} \approx 1.1mm$. This extinction trend is opposite to that displayed in nitrogen-diluted experiments, but in agreement with the normal gravity experiments. The k for the binary array (0.75 mm^2/s) was smaller than k for the single droplet (0.90 mm^2/s), although there is only a short time period in the single droplet experiment to calculate k. The flame height for the binary array was larger than the flame height for the single droplet. Further tests showed that the flames surrounding the binary droplet array at $L \approx 8, 12 \ mm$ (merged flames existed for both spacings) both extinguished at droplet diameters smaller than the single droplet. The extinction behavior at $L \approx 24mm$, however, was nearly identical to that of a single droplet.

The observed difference between the two ambients is attributed to the importance of radiative loss. The nitrogen/oxygen tests had larger, weaker flames, and smaller burning rates and consequently were affected more significantly by radiative loss from the flame zone compared to the helium/oxygen tests.

Numerical Modeling

The numerical model of the single droplet (numerical modeling of the binary array is in progress) is based on the model of the candle flame [12]. The model is one-dimensional and transient in both the liquid and gas phase. The gas-phase model assumes: one-step, second-order overall Arrhenius reaction, constant specific heats and thermal conductivity, constant Lewis number for each species (although different species can have different, constant Lewis numbers), ideal gas behavior, and no buoyant force. Flame radiative losses from carbon dioxide and water vapor are accounted for by a gray gas treatment. Dietrich and co-workers [13] provide complete details about the numerical model, solution procedure and a more complete listing of the results.

Figure 2 shows a comparison of an experiment in a $120mmHg$, 0.15 oxygen mole fraction ambient with the predictions of the numerical model. The D_{ext} are $0.76mm$ and $0.69mm$ for the experiment and model, respectively. The agreement between the model and experiment is very good. The predicted flame diameter and temporal behavior of the flame size are very close to the experiment. The only exception is near the end of the test when the model predicts that the flame size and standoff decrease until extinction, whereas the experiment shows that the flame standoff increases continuously until extinction.

The numerical model correctly predicts many of the observed experimental trends. Furthermore, quantitative agreement is good for the temporal behavior of both the droplet and flame. This agreement requires suitable values for the average gas-phase thermo-physical and chemical kinetic properties. The fact that the droplet history agrees is not surprising, since even the simplest formulation will produce good estimates of the burning rate constant as long as reasonable properties are used in the formulation. Simplified models, however, do not predict accurate flame sizes, and the current model provides reasonable agreement for flame size as a function of time. The model does not predict the experimentally observed pressure dependence of extinction. This is due to the simplified kinetics scheme, although it may be possible to change the pressure dependence of the single step scheme to get better agreement. One surprising result of the model was the sensitivity of the extinction conditions to the ignition parameters. The igniter location, energy and duration must closely match the experimental values such that the model accurately predicts both the pre-ignition vaporization behavior and ignition time (first appearance of a flame).
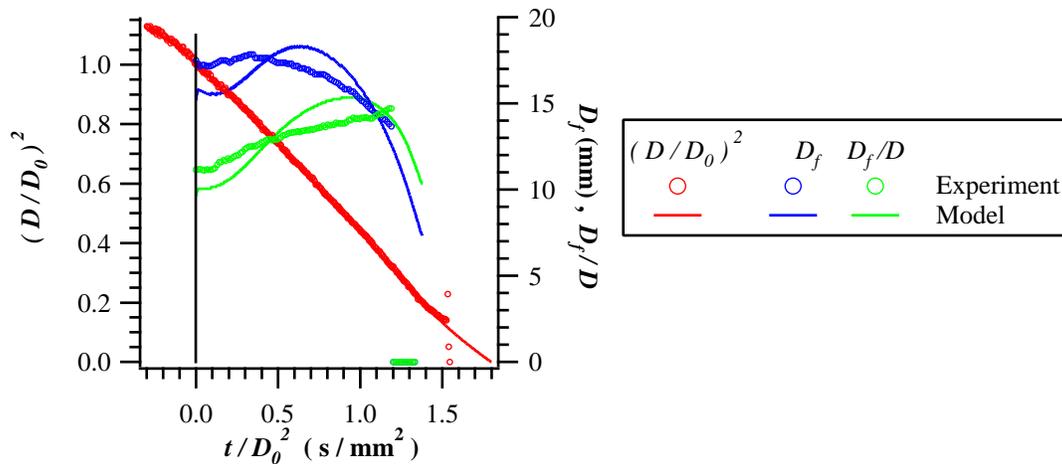
Figure 2: Experiment and numerical model comparison for a single ($D_0 \approx 1.8mm$) droplet burning in a 0.15 oxygen mole fraction, $120mmHg$, nitrogen-diluted ambient in microgravity.

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