COMBUSTION OF INTERACTING DROPLET ARRAYS IN A MICROGRAVITY ENVIRONMENT*

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Introduction

This research program involves the study of one and two dimensional arrays of droplets in a buoyant-free environment. The purpose of the work is to extend the database and theories that exist for single droplets into the regime where droplet interactions are important. The eventual goal being to use the results of this work as inputs to models on spray combustion where droplets seldom burn individually; instead the combustion history of a droplet is strongly influenced by the presence of the neighboring droplets.

Recently, Annamali and Ryan (ref. 1) have summarized the current status of droplet array, cloud and spray combustion. While no attempt will be made to duplicate this work here, there are several relevant ideas that should be mentioned. There a number of simplified theories (refs. 2-6), and a small number of detailed numerical studies (refs. 9 and 10) of droplet vaporization/combustion where multiple droplet effects are significant. These theories all neglect the effect of buoyancy. Experimentally, all studies to date show how important the effect of buoyancy is, in fact, it becomes the dominant transport mechanism in the problem. Only the works of Law and co-workers were performed in an environment where buoyancy effects were small (refs. 11 and 12), and the authors were limited to studying combustion in high oxygen index, low pressure ambient environments.

The emphasis of the present investigation is experimental, although comparison will be made to existing theoretical and numerical treatments when appropriate. Both normal gravity and low gravity testing will be employed, and the results compared. The work to date will be summarized in the next section, followed by a section detailing the future plans.

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* Research initiation date: 4/1/91.

Work to Date

Normal Gravity Droplet Combustion Chamber

As presented in the previous section, normal gravity testing will be employed in this work. Toward this end a combustion chamber to study the burning of single droplets and droplet arrays was designed and built. The chamber can handle absolute pressures from 0 - 1 atm, and is equipped with a gas mixing system so that the ambient pressure and gas composition can be accurately controlled. Inside the chamber, droplet(s) are suspended from 125 μm quartz optical fibers with a precisely controlled[1] 250 μm bead placed on the end. Droplets are placed on the end of the fiber with a hypodermic tube attached to a rotary solenoid. Ignition is accomplished with a length of .010 inch Kanthal (Aluminum alloy) wire heated with a current of approximately 4 amps. The hot-wire is attached to a linear solenoid, and is removed immediately after ignition. Photographic images are obtained by two orthogonal views; one a backlit view from which the droplet size as function of time is obtained, and the other from which the flame dynamics are captured. The entire droplet dispense/ignition and photographic process is controlled with a time delay relay circuit.

One of the first uses of the combustion chamber was to evaluate the suitability of an intensified array camera to image the flame in the ultra-violet region of the spectrum as opposed to the visual image usually obtained. This work is in support of the Droplet Combustion Experiment (M. Vehda-Nayagam, project scientist). Methanol and n-heptane droplets were burned in ambient environments of Helium/Oxygen and Nitrogen/Oxygen at atmospheric and sub-atmospheric pressures. The flame images were recorded with the intensified array camera (UV Nikkor lens, quartz viewing window) and regular black and white video camera. Most of the video with the intensified camera was taken with a 310 nm bandpass filter in place. The purpose was to attempt to image the OH emission and compare that image with the visual image.

Figure 1 shows two images, the one on the right being that obtained with the intensified array camera, and on the left from the black and white video camera at the same time. This was an n-heptane droplet burning in a 35% Oxygen/65% Helium (mole fraction), and a total pressure of 0.75 atm. As is easily seen, the two images are very different, with a measurement of the flame diameter and shape being very different depending on the camera used. At the present time, no definitive conclusions can be drawn from the existing data, as further analysis of the existing data is needed, in addition to more data with a color video camera and possibly more filters.

Single droplets of methanol and n-decane were studied in high oxygen, low pressure ambients. The purpose was to duplicate some of the work of Law and co-workers (refs. 13 and 14). The result of one of these tests is shown in Fig. 2 with the square of the normalized droplet diameter shown as a function of time. "the burning rate constant, defined as the best linear fit between the two dotted lines in Fig. 2, was 0.84 mm^2/sec. This was somewhat lower than the value reported by Chung and Law. As also seen in Fig. 2, flame extinction occurs before the droplet has completely vaporized (fuel was visible on the fiber). The extinction diameter for this droplet was approximately 300 μm. This droplet size was very close to the suspending fiber bead size, however, so fiber interference effects were no doubt important.

For the same oxygen concentration and fuel as shown for the test in Fig. 2, but higher pressures (0.3 atm), microexplosions were observed. A sequence of frames from before, during, and after a microexplosion are shown in Fig. 3. In the beginning, droplet burning was normal, but then the liquid disruption begins and finally the explosion. After the explosion, normal droplet burning

1 The ability to accurately control the size of the bead is critical when performing the droplet array studies so that the droplets in the array are as identical as possible (ref. 10).

continued if any liquid remained on the fiber. These microexplosions seem to originate on the fiber indicating fiber interference. Microexplosions also occurred at 0.2 atm, but were less severe, and typically occurred later in the droplet lifetime. No microexplosions were seen at 0.1 atm.

More recently, work has started on burning multiple droplets. Figure 4 shows two droplets initially 1 mm in diameter separated by approximately 6 mm. The fuel was n-decane, and the pressure was 0.1 atm. Three pictures are shown at different times in the droplet lifetime. As expected, early in the burning history, the two flames merge into a single flame, and later in the lifetime the two droplets experience less interactions, and burn individually. Because of the low pressure in the flames in Fig. 4, buoyancy effects were reduced (not eliminated) and the flames were more spherical.

Reduced Gravity Droplet Combustion

Progress in low gravity has been limited by problems with the experimental apparatus. The major development in this area has been utilizing extremely small (10-15 μm) Si-C fibers to suspend droplets. These fibers are an order of magnitude smaller than the fibers used in most suspended droplet studies. Figure 5 shows an n-decane droplet suspended from one of these fibers. This drop was created in low gravity by stringing one of these fibers between the two deployment needles in the droplet combustion facility of the 2.2 second drop tower. As can easily be seen, the deviation from spherical symmetry is very small, with the fiber being barely visible. Figures 5 also shows the backlit view of the same droplet during combustion. One of the major advantages of using these fibers is the potential to perform thermometry measurements in the gas phase of sootless droplet burning (ref. 15). This is particularly useful when studying extinction phenomena; enabling one to identify flame position, change in flame temperature, and flame dynamics at extinction.

Given the encouraging results using these fibers, a new experimental apparatus for the low gravity facilities is being developed. The experiment is designed to study one and two dimensional arrays of droplets suspended by the Si-C fiber. The current status of the rig is that the design and construction are nearly complete. Integration into a drop frame for the 2.2 second drop tower is under way. Initial testing is expected to begin in the beginning to mid-October.

Another accomplishment is the development of an automatic data processing technique to measure droplet size as a function of time from drop tower data. The technique is similar to that of Choi et al. (ref. 16) and involves grabbing a frame from film (or video) and digitizing it. The edge of the droplet is then detected by one of two methods (absolute intensity or intensity gradient), and the area averaged droplet diameter is determined.

Future Work

Work in the remaining 2+ years of the grant will continue in both the normal gravity test cell, and the low gravity apparatus. Several minor improvements will be made to the normal gravity apparatus. The ignition system will modified, possibly even incorporating a spark ignition system; the ultimate goal being to reliably ignite a droplet in the shortest amount of time with as little disturbance as possible. This work will be done in conjunction with the Droplet Combustion Experiment (DCE) science team (F. Williams, F. Dryer, and M. Vehda-Nayagam). The fuel system will be improved to allow accurate delivery of multiple droplets simultaneously. This new fuel system is nearly complete.

Another area of work that will be done in conjunction with the DCE science team, is on improved flame imaging. Further testing will be done with the intensified array video camera, a color and black and white video camera to determine the best method of imaging a droplet flame. For some of these tests, a small Si-C fiber will be strung across the droplet (not supporting the droplet) and the luminous image of the fiber during combustion will be recorded. The image of the 'glowing' fiber will be compared to the visual flame images obtained with the video cameras.

In addition, work will continue on attempting to obtain temperature measurements from these fibers. Currently, a model is being developed to correct the temperature of the fiber for radiation, conduction and convective losses. The first experimental work will be conducted in the normal gravity facility, and if the results are promising, it will be incorporated into the drop rig. Even if absolute temperature measurements are not possible, these fibers will enable a qualitative measurement of location of the maximum flame temperature, change in flame temperature as a function of time and flame width.

Normal gravity work in the next year will be focussed on studying single droplets and linear droplet arrays. Two fuels will be employed. The first will be methanol, the second n-decane. The major variables will be the inter-droplet spacing, ambient oxygen concentration, pressure and diluent (helium or nitrogen). The results of these studies will be compared to similar tests that will be conducted in the 2.2 second drop tower with the new droplet combustion apparatus.

References

1. Annamalai, K. and W. Ryan. "Interactive Processes in Gasificcation and Combustion. Part I: Liquid Drop Arrays and Clouds," *Progress in Energy and Combustion Science* **18**, 1992, 221.
2. Brzustowski, T.A., E.M. Twardus, S. Wojcicki and A. Sobiesiak. "Interaction of Two Burning Fuel Droplets of Arbitrary Size," *AIAA Journal* **17**, No. 11, 1979, 1234.
3. Labowsky, M. "A Formalism for Calculating the Evaporation Rates of Rapidly Evaporating Interacting Particles", *Combustion Science and Technology* **18**, 1978, 145.
4. Labowsky, M. "Calculation of the Burning Rates of Interacting Fuel Droplets," *Combustion Science and Technology* **22**, 1980, 217.
5. Marberry, M., A.K. Ray and K. Leung. "Effect of Multiple Particle Interactions on Burning Droplets," *Combustion and Flame* **57**, 1984, 237.
6. Samson, R., D. Bedeaux and J.M. Deutch. "A Simple Model of Fuel Spray Burning II. Linear Droplet Streams," *Combustion and Flame* **31**, 1978, 223.
7. Umemura, A., S. Ogawa and O. Nobunori. "Analysis of the Interaction Between Two Burning Droplets", *Combustion and Flame* **41**, 1981, 45.
8. Raju, M.S. and W.A. Sirignano. "Unsteady Navier-Stokes Solution for Two Interacting, Vaporizing Droplets", AIAA-87-0300, AIAA 25th Aerospace Sciences Meeting, Reno, Neveda, 1987.
9. Tal, Reuven and W.A. Sirignano. "Cylindrical Cell Model for the Hydrodynamics of Particle Assemblages at Intermediate Reynolds Numbers", *American Institute of Chemical Engineers Journal* **28**, No. 2, 1982, 233.
10. Miyasaka, K. and C.K. Law. "Combustion of Strongly Interacting Linear Droplet Arrays", *Eighteenth Symposium (International) on Combustion* / The Combustion Institute, 1981, 283.
11. Xiong, T.Y., C.K. Law, C.K. and K. Miyasaka. "Interactive Vaporization and Combustion of Binary Droplet Systems", *Twentieth Symposium (International) on Combustion* / The Combustion Institute, 1984, 1781.
12. Chung, S.H., and C.K. Law. "An Experimental Study of Droplet Extinction in the Absence of External Convection," *Combustion and Flame* **64**, 1986, 237.
13. Law, C.K., S.H. Chung and N. Srinivasan. "Gas-Phase Quasi-Steadiness and Fuel Vapor Accumulation Effects in Droplet Burning", *Combustion and Flame* **38**, 1980, 173.

14. Vilimpoc, V. and L.P. Goss. "SiC-Based Thin-Filament Pyrometry: Theory and Thermal Properties," *Twenty-Second Symposium (International) on Combustion / The Combustion Institute*, 1988, 1907.
15. "Choi, M.Y., F.L. Dryer, J.B. Haggard, M.H. Brace. "Further Observations on Micro-gravity Droplet Combustion in the NASA-Lewis Drop Tower Facilities: A Digital Processing Techniqui for Droplet Burning Data," Third International Colloquium on Drops and Bubbles, Monterey, California, 1988.

Figure 1. Comparison of images from a black and white video camera (left) and intensified array video camera with 310 nm bandpass filter in place. n-Heptane in a 0.75 atm, 0.35/0.65 Oxygen/Helium (mole fraction) ambient.

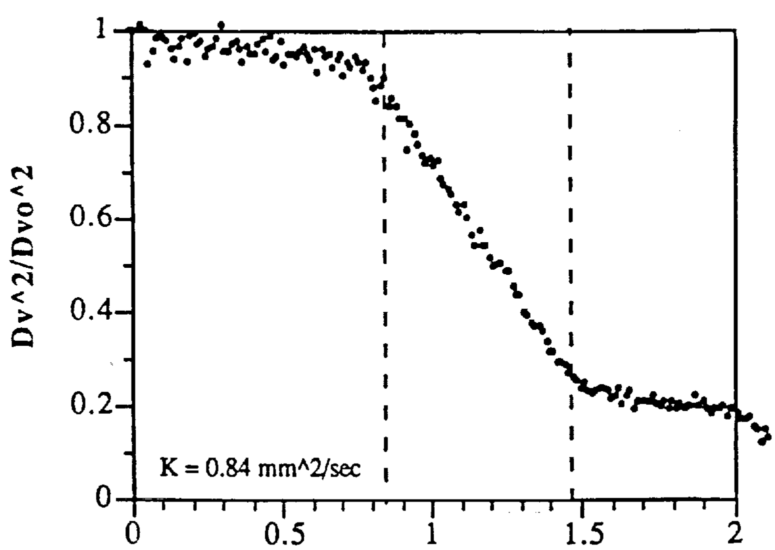

Figure 2. Normalized volume averaged droplet diameter as a function of time for n-decane burning in a 0.1 atm, 0.5/0.5 Oxygen/Nitrogen (mole fraction) ambient.

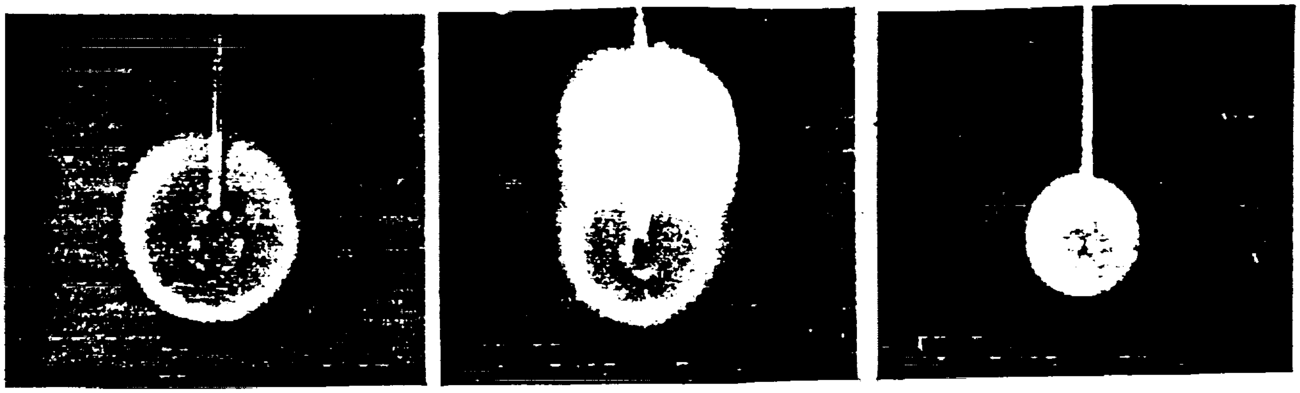

Figure 3. n-Decane in 0.3 atm, 0.5/0.5 Oxygen/Nitrogen ambient, before (left), during (center) and after (right) microexplosion.

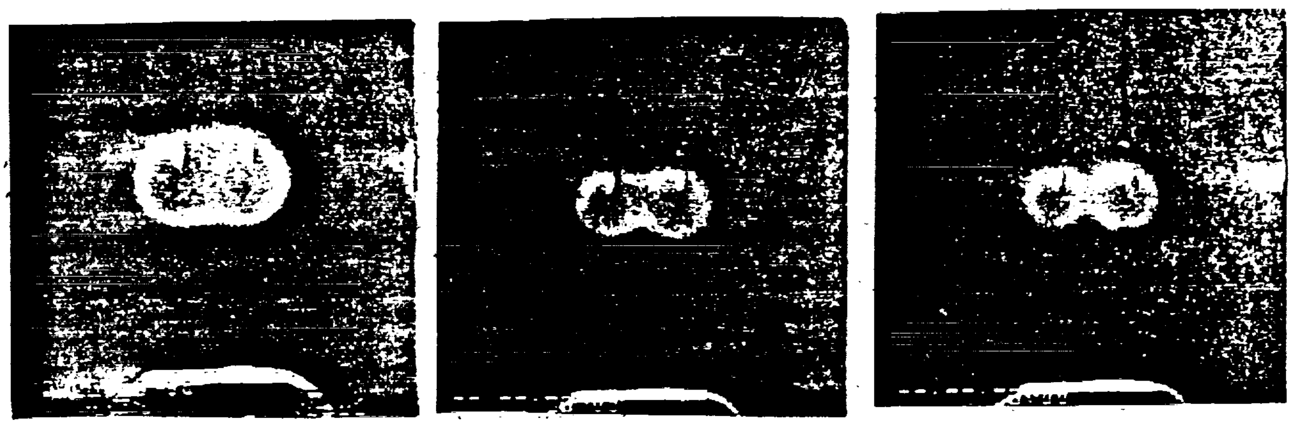

Figure 4. Two n-decane droplets burning in air at 0.1 atm on 125 μm fibers at three times during the burning history.

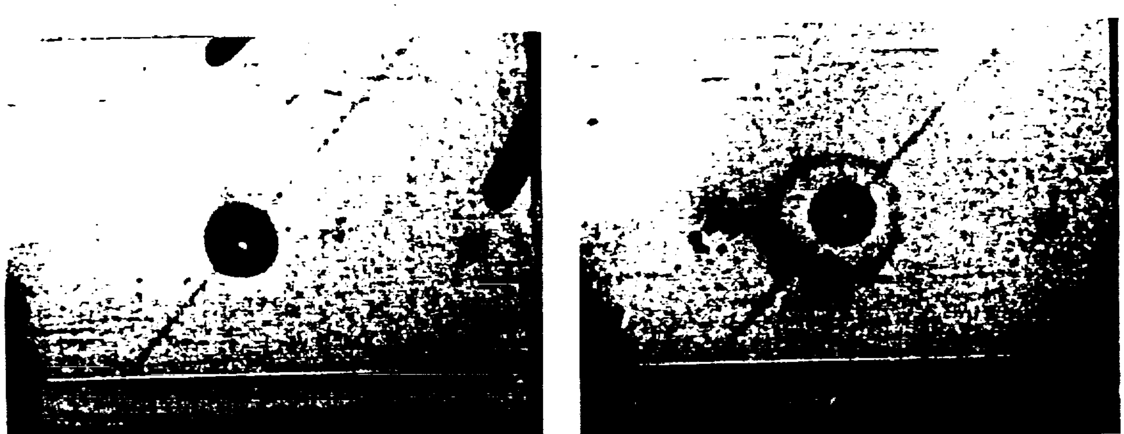

Figure 5. n-Decane droplet in air at 1 atm supported on a 10-15 μm Si-C fiber before (left) and during combustion (right).

COMMENTS

Question (C.T. Avedisian, Cornell University): In looking at your video of the combustion of droplet arrays in microgravity using fiber supported droplets, some work that Brzustowski and co-workers did in the late 70's on unsupported droplet arrays in microgravity came to my mind. Do you intend to include a study of unsupported droplet arrays in your work?

Answer: Not in the immediate future (1 year). We are, however, considering looking at unsupported arrays in the last year of funding.