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CONTINUING STUDIES OF LIQUID PROPELLANT DROPS IN HOT, HIGH-PRESSURE ENVIRONMENTS

RICHARD A. BEYER

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Drops of LP 1846 have been heated in the gases and flames above burning solid propellants at pressures up to 20 MPa (3000 psi). Semi-quantitative measurements of drop lifetime versus pressure and drop diameter have been made. Although limited by uncertainty in the visualization, these observations show that the trend toward shorter drop lifetime with increasing pressure seen at lower pressures continues in this regime. Visible light emission from the evolved gases and near the drops was recorded during heating under some conditions. Microexplosions of the drops were not observed.

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I. INTRODUCTION

The understanding of the processes in a regenerative liquid propellant (LP) gun from injection to final heat release cannot be complete without a knowledge of the behavior of individual drops under conditions of ignition and combustion. In our earlier work we have studied the behavior of drops of hydroxylammonium nitrate (HAN) and the HAN-based propellants LP 1845/LP 1846 in hot flows at atmospheric pressure[1] and at pressures up to 8.6 MPa (1250 psi).[2] In the present study we have extended these observations to higher pressures and temperatures. In particular, a major goal was to ignite the drops as indicated by the emission of visible light.

While electric resistance heating of nitrogen gas which was then flowed over the drop was used quite successfully at the lower pressures, difficulty was encountered with that technique at these pressures. Although that technique will be further pursued, it will not be discussed in this paper. A limited number of observations were made with a drop suspended less than a millimeter from a hot wire. The main reason for attempting this heating was as an alternative method of drop ignition. In the majority of the work discussed here, drops of LP 1846 have been subjected to the hot gases and flames from burning solid propellant. This technique provides hot temperatures with a rapid rise rate and also more nearly simulates the gas composition in a gun. In spite of a strong desire to obtain information about both gas and liquid phase chemical processes, these observations are limited to high speed imaging.

II. EXPERIMENTAL

The basic layout of this experiment remains much the same as reported previously.[2] A new pressure vessel specifically designed to allow for safe operation at higher pressures than earlier versions was used here. By decreasing the interior volume and using sapphire windows, safe operation in the laboratory up to 48 MPa (7 Kpsi) was made possible. The window geometry was also changed to give optical access from all four sides in anticipation of laser spectroscopic probes of these phenomena. For the work reported here, the maximum pressures were limited by the pressurization system to about 20 MPa (3000 psi).

A simple fixture, shown in Figure 1, was made to hold the drop and thermocouple in position and contain the solid propellant grain. The hole for the solid propellant was 0.125 in. (3.2 mm) in diameter. The drop was suspended about one millimeter above the burnt gas exit port. The chamber was pressurized with nitrogen; the solid propellant was then electrically ignited and the events recorded with strong, continuous backlighting at typically 2000 frames/sec with a high speed video system (Spin Physics Model SP2000). Final pressures were not recorded; the pressure increase due to the solid burning was calculated to be less than 10% and was probably not important here. The solid propellant used was NOSOL 363. Small grains were made 11 mm long with either 0.125 inch (3.2 mm) diameter or 1/16 inch (1.6 mm) square. The larger of these provided a hotter flow with full flame exposure to the region of the drop. The smaller size was used with the thermocouple measurements; it also provided reasonable temperature rises while keeping gas velocity and turbulence to a level where visibility remained reasonable. The distance from the grain to the drop also was varied to change the temperature

at the drop. The sides of the grains were inhibited with a coating of clear cement which was only partially effective. Ignition of the grain was via a nichrome wire embedded about one millimeter into the end.

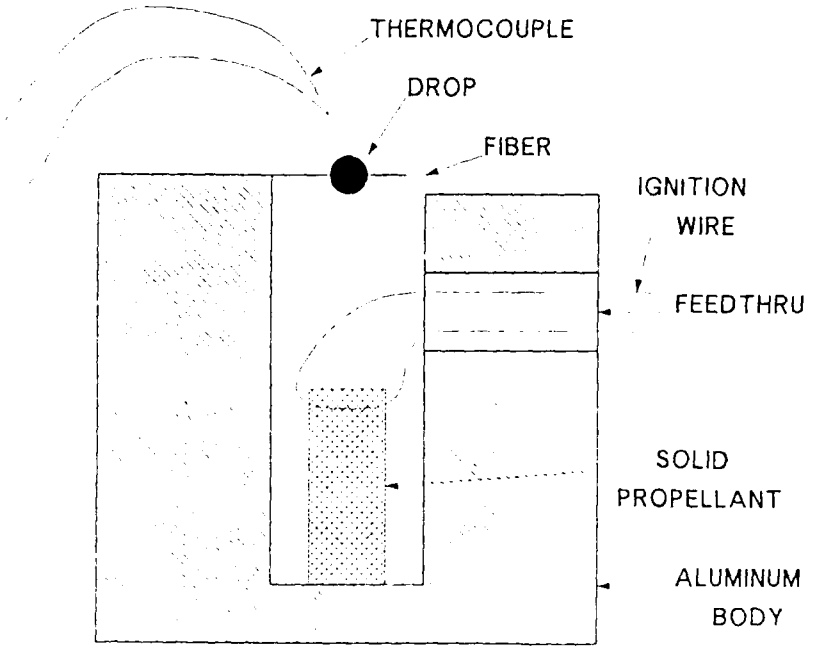

Figure 1. Schematic Drawing of Fixture Used in Most of These Observations

Typical temperature profiles as seen just above the drop position are shown in Figure 2. Temperatures were measured with a 50 μm chromel-alumel thermocouple mounted approximately two millimeters above the drop. Because of frequent damage to the thermocouples from solid propellant flames, they were not deployed in every case. Typical flow velocities in the drop region were measured at about 0.3 m/sec, resulting in a moderately turbulent flow. However, with the strong index of refraction gradients present in a hot flow at these pressures, even slight turbulence makes viewing conditions less than desirable.

The liquid propellant for all of these studies was LP 1846. The drops varied in size from 100 to 600 μm diameter. Drops were suspended on 50 micrometer diameter fused silica fibers, as shown in Figure 1. The drops appear to be cylindrically symmetric along the axis of the fiber, due to surface tension. The larger drops are nearly spherical before heating, except for a meniscus at the fiber interface.

III. OBSERVATIONS

The drops heated in proximity of a hot wire showed two characteristics. The first was that drop lifetime was longer than with convective heating by a factor of two or more. The second was that the drops vaporized into a very

opaque and dense cloud of vapor when heated in this method. There was no evidence of internal gas bubble formation or loss of opacity prior to the gasification. In most cases the vaporization event was complete in less than 0.5 msec following the heating induction period, with a few very small droplets remaining. Because the heat transfer to the drop is both radiative and convective, no attempt was made to characterize the gas temperature outside the drop. The possible reactivity of the LP with the thermocouple material discouraged measuring internal drop temperatures.

Two temperature profiles recorded above the drop mounting position are shown in Figure 2. Both were recorded for pressures near 19 MPa (2750 psi) of nitrogen gas with the smaller propellant grains. The photography strongly suggests that the hot flow seen by the drops is dominated by the burnt gases from the solid propellant. Ignition of the first was probably not as vigorous as with that of the second. These two curves demonstrate some of the variability of this technique for heating. The curve shown in Figure 2a is near the limit of rapid rise without full flame impingement on the drop. The 410 μm drop exposed to the flow of Figure 2a lasted about 37 msec, going away at the point indicated by the arrow on the curve. Thus the drop experiences the full range of temperatures from ambient through 1200°C during its lifetime. Similarly, in Figure 2b, which has been shifted to the right to avoid overlap, the 28 msec lifetime of the 540 μm drop is noted. Although this drop is larger and in a cooler flow, its lifetime is shorter. Drop disappearance in these and most other cases was by drop shrinkage over a period of about 2 msec or less. No loss of opacity was noted prior to this time when the drops started to change size and shape. Because of the low image quality, it was usually not possible to distinguish gases leaving the drop from the thermal flow disturbances. In some cases the drops become deformed, elongated, or move along the fibers as they react. It was not unusual for the drops to leave the fiber; this event usually occurred after substantial heating and is probably related to reduced surface tension in the heated liquid. In many cases the fused silica fiber was bent upward without breaking by the hot flow, usually after the demise of the drop. In one such case a 400 μm drop stayed on the fiber without major change as it bent.

Visible emission was observed in a few cases as drops vaporized in the 20 MPa runs. In one case a residue was also left on the fiber which glowed brightly for 2 msec. In cases where the drops were in the secondary flame of the solid propellant, results were also quite variable. In some cases the drops merely decreased in size; in others the flames formed a bright outline of the drop as it was consumed. Since the solid burned longer than the liquid, it was not clear that the drop was ignited.

Attempts were made to quantify the behavior of the drops as they were heated in the flow. The first of these is shown in Figure 3. Here the the apparent diameter of the drop heated in the flow in Figure 2b was obtained by computer edge fitting of the drop image with a circle. Two trends appear in this plot. One is an apparent oscillation in drop diameter; the second is an overall increase in diameter with time. The oscillation may well be due to thermal image distortion and will not be addressed further until better data are available. The increase in diameter does appear to be real. There is no evidence of internal bubble formation or change in opacity during this time. The drop did become opaque, deformed, and disappeared in the three frames (1.5 msec) following the last plotted point.

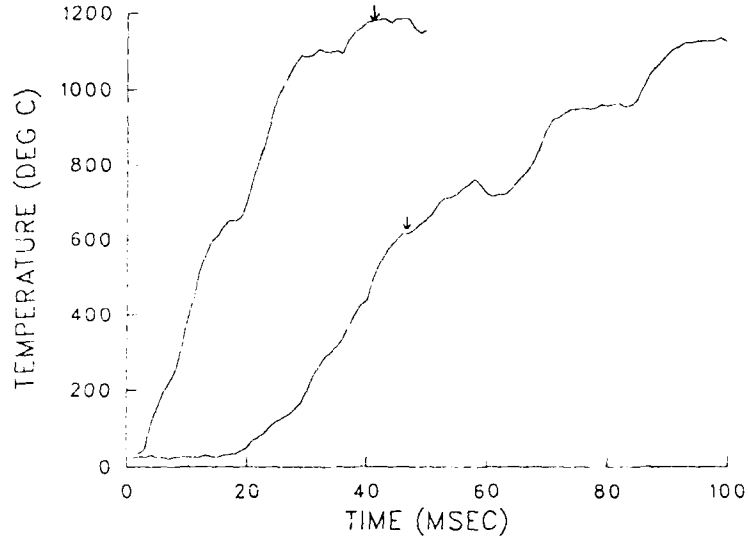

Figure 2. Typical Rapid-Rise Temperature Profiles as Recorded Above the Drops with Solid Propellant Heating Near 19 MPa. Arrows indicate time of drop disappearance for (a) 410 μm and (b) 540 μm diameter drops.

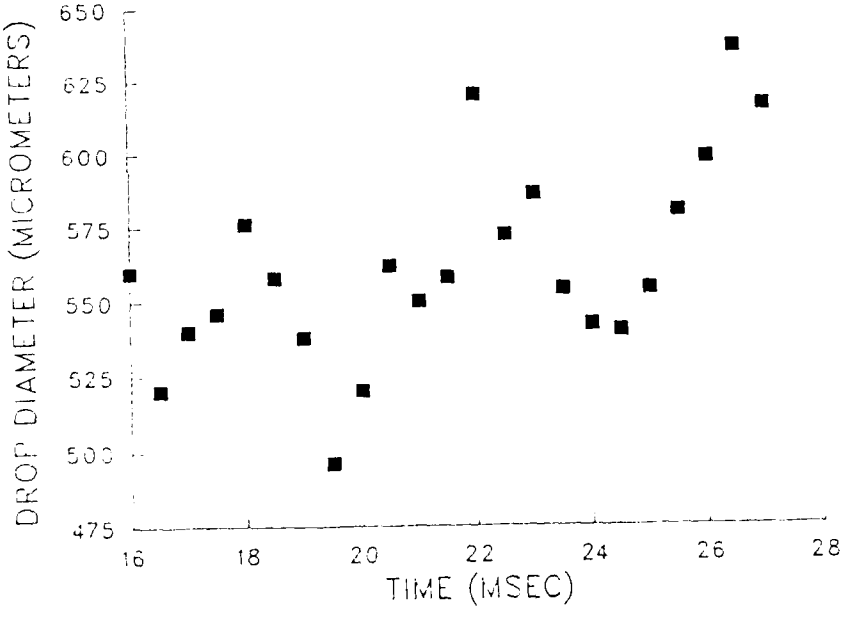

Figure 3. Computer Fit of Drop Diameter Versus Time for the Drop Heated in Flow of Figure 2b. Time zero is at first sign of hot flow at drop position.

The other attempt at characterization of behavior was to measure the drop lifetime versus initial diameter under conditions where the solid propellant grain position and size was held reasonably constant. The results of two such trials are shown for 8.8 MPa (1275 psi) and 14.5 MPa (2100 psi) in Figure 4. As can be seen, the reproducibility is not good.

IV. DISCUSSION

Although a major goal of the present study was the ignition of drops in order to characterize such parameters as the extent of liquid phase chemistry, the location of ignition, and the structure of the subsequent flame, it is not clear that any drops have yet been ignited here. As mentioned, a few drops have burned under the influence of solid propellant secondary flames, but it is not clear that their combustion would have continued without this stimuli. The observation of some visible light in the wake of disappearing drops suggests that the gases evolving from the drops may be marginally ignitable under the flow conditions existing here.

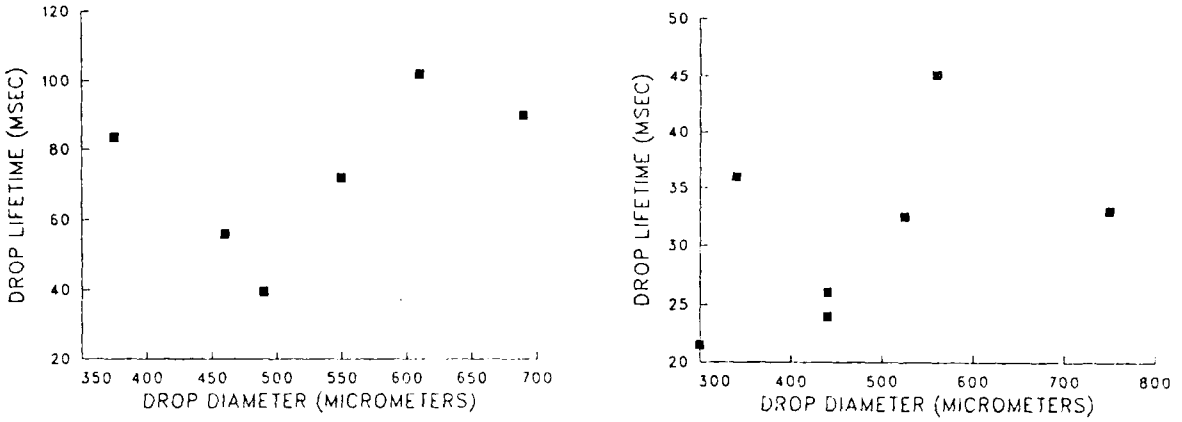

Figure 4. Time from First Heating to Disappearance of Drops for a Range of Diameters at (a) 8.8 MPa and (b) 14.5 MPa

The explanation of the apparent drop expansion shown in Figure 3 is difficult. It is quite possible that the drop shape is oscillating and/or rotating with some complex spheroidal/elipsoidal geometry. The image, interpreted as spherical from one direction, could yield the plotted values. The amount of diameter increase is too great to be explained by simple thermal expansion. There is no evidence of liquid phase chemistry, such as bubble formation or change in light transmission, as was seen at lower pressures in the earlier studies.[2] It is possible that there are changes in the complex intermolecular interactions of the liquid and thus of the density. The degree of expansion is certainly greater than seen at lower pressures prior to bubble formation, as for example in Figure 8 of Reference 2. As with the oscillations, this point requires better data with less turbulence and thermal distortion to be resolved.

The actual physical event during the disappearance of the drops is not well defined for these observations. That is, it is not clear if the outer surface of the drop is being physically or reactively ablated, if it is chemically reacting to volatile liquid or to gases, or even if the critical point of the liquid is being exceeded. Without analysis of the changes in liquid composition, especially near the surface of the drop, it is not clear how to differentiate these possibilities. Although in the many events that

have been recorded some look more like one of these possibilities than another, none can be ruled out definitively.

Perhaps the main conclusion that can be reached from the data plotted in Figure 4 is that the drops do not see the same environment even when the grains and ignition conditions are duplicated reasonably well. The greatest difference in these experiments is probably ignition of the grain, depending on the interaction of the wire with the solid propellant. In this figure there are clearly trends toward longer times for larger drops or with lower pressures, as seen before.[2] Again, more observations are required.

V. FUTURE STUDIES

Studies using burning propellant for the heat source remain of major interest because they provide a gas composition more nearly like that encountered in the gun environment, especially with regard to water vapor concentration. Thus efforts will continue to provide a reproducible and well characterized hot flow from such sources. One approach not yet tried is to use a small amount of liquid propellant. With this technique, a reproducible amount could be reliably metered and the ignition/propellant interface could be made more reproducible. Of course the liquids may only burn sufficiently well at the upper end of the pressures of interest here.

Attempts will continue to make an electrically heated flow chamber that can produce an environment independent of pressure. In addition, the desirability of freely falling drops suggests the injection of drops into a preheated region. Such injection involving a minimum quantity of LP for safety reasons have been the subject of some effort here without success. These will continue.

A major parameter of interest remains the degree of liquid phase chemistry in the drops during heating as well as the composition of gases evolved from the drops as they react. Preliminary experiments have begun to apply Raman spectroscopic techniques to the drops in the manner of Chang, et al.,[3] but with the enhancement of using a copper vapor laser at up to 20 KHz repetition rate to give good time resolution. These efforts and those of gas phase spectroscopy near the drops require a somewhat less turbulent environment to allow sufficiently accurate aiming of the laser beam. The achievement of these measurements will be quite difficult but they do appear to be possible.

Additional efforts include increasing the operating pressure of the chamber to about 6000 psi (41 MPa). This increase requires only changes in the gas supply system. The copper vapor laser will also be used more extensively for imaging in order to make more definitive observations.

Observations made in our laboratory on related experiments have suggested that a major source of variability in the present measurements is due to changes in water content of the LP drops during the time between placement of the drop on the fiber and the experiment. Efforts to measure and/or control this parameter will be made if possible.

VI. CONCLUSION

This study has shown the difficulty of making detailed observations of individual drops of LP under conditions of high temperature and pressure. At the same time it is clear that with refinement these observations should yield data which will characterize the response of these drops during injection into a gun during at least the ignition phase. The pressure and temperature trends of the previous studies have been extended and behavior appears to be consistent. The possibility of the drop behavior being related to the proximity of the critical point of these liquids remains an unknown. Studies of the near future should provide quality data to provide answers for these questions.

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