COMBUSTION OF HAN-BASED MONOPROPELLANT DROPLETS IN REDUCED GRAVITY

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INTRODUCTION

Hydroxylammonium nitrate (HAN) is a major constituent in a class of liquid monopropellants that have many attractive characteristics and which display phenomena that differ significantly from other liquid monopropellants [1]. They are composed primarily of HAN, H_2O and a fuel species, often triethanolammonium nitrate (TEAN). HAN-based propellants have attracted attention as liquid gun propellants (e.g., [1]), and are attractive for NASA spacecraft propulsion applications [2]. A representative propellant is XM46. This mixture is 60.8% HAN, 19.2% TEAN and 20% H_2O by weight. Other HAN-based propellant mixtures are also of interest. For example, methanol and glycine have been investigated as potential fuel species for HAN-based monopropellants for thruster applications [3].

In the present research, experimental and theoretical studies are performed on combustion of HAN-based monopropellant droplets. The fuel species considered are TEAN, methanol and glycine. Droplets initially in the mm size range are studied at pressures up to 30 atm. These pressures are applicable to spacecraft thruster applications [2]. The droplets are placed in environments with various amounts of Ar, N_2, O_2, NO_2 and N_2O. Reduced gravity is employed to enable observations of burning rates and flame structures to be made without the complicating effects of buoyant and forced convection. Normal gravity experiments are also performed in this research program.

The experiment goals are to provide accurate fundamental data on deflagration rates, gas-phase temperature profiles, transient gas-phase flame behaviors, the onset of bubbling in droplets at lower pressures, and the low-pressure deflagration limit. Theoretical studies are performed to provide rational models of deflagration mechanisms of HAN-based liquid propellants. Besides advancing fundamental knowledge, this research should aid in applications (e.g., spacecraft thrusters and liquid propellant guns) of this unique class of monopropellants.

NORMAL GRAVITY EXPERIMENTS

Normal gravity experiments were performed: (1) to perform screening of the propellant formulations that might be investigated in microgravity; and (2) to provide baseline normal-gravity data to be compared with the reduced-gravity data. A summary of the results from these experiments is provided below. Details on these experiments are available elsewhere [4].

The normal-gravity experiments were performed at UC Davis using an available pressure vessel. This vessel was pressurized to as high as 10 atm with either N_2 or air. Individual droplets of various formulations (HAN-water, XM46, HAN-glycine, HAN-methanol, methanol, and TEAN-water) were deposited onto a quartz fiber using a computer-controlled assembly. A wire-loop heating element was used as an igniter, and a high-speed video camera was used to image droplet shape changes at frame rates as high as 1000 frame/s. In addition, droplet and flame behaviors were imaged using a conventional CCD camera as well as a Xybion intensified-array (ICCD) camera. The ICCD camera employed a 310 nm interference filter as well a UV lens system, thus allowing observation of UV emissions from OH radicals. A special UV-transmissive quartz window was utilized in the pressure vessel to allow clear imaging of OH emissions. Schematics of the experimental setup are shown in Figs. 1 and 2.

These experiments demonstrated that the different monopropellant combinations display very different behaviors. For example, HAN-water droplets (13 molar) did not produce a gas phase flame under any conditions. However, these droplets exhibited strong bubbling throughout their lifetimes. A representative image of a HAN-water droplet is shown in Fig. 3, where bubbles can be seen in the droplet. The bubbles are likely a result of liquid-phase chemical reactions as well as chemical stratification in the liquid. The igniter is visible in Fig. 3 (beneath the droplet).

In contrast, the XM46 droplets could be ignited in air (but not N_2). The flames were generally of very short duration relative to the droplet lifetime, with flames appearing towards the end of the droplet lifetime. Figure 4 shows droplet and flame lifetime data for XM46 droplets with initial diameters of about 1.6 mm (based on droplet volume). Flame durations, as sensed by the thermocouple, were about an order-of-magnitude shorter than the droplet lifetimes. These experiments were performed such that the temperature of the igniter-produced hot gas field around the droplets, as measured by a thermocouple, was nearly constant for all droplets and all pressures. The XM46 droplets generally exhibited bubbling throughout much of their lifetimes (droplet lifetimes were defined to be the time elapsed between energizing the igniter and the end of the flame lifetime, which generally coincided with the disappearance of the droplet).

Visible emissions from XM46 flames were yellowish in color, suggesting that soot was present, though the yellow coloration could be radiation from hot TEAN particles that might be produced during the combustion [5]. Imaging of UV emissions from the XM-46 flames indicated that the flame zones could be substantially larger than would be anticipated for simple diffusion flames. High-speed imaging of the XM46 droplets also showed that organized structures were sometimes present in the gas phase when the droplets were bubbling. For example, Fig. 5 shows a toroidal structure, which is likely a vortex, outside of a droplet. These structures appeared to form when material was locally ejected from the surface of a droplet. The gas-phase structures likely have aerosol particles in them, rendering them visible in the backlit images. The toroidal vortices were less common at high pressure because the gas flows became turbulent, disrupting the organized flows.

The 1-g experiments also showed that HAN-methanol droplets (with various amounts of HAN and water) could be ignited in air. An interesting characteristic of these experiments is that the flames displayed yellow coloration when HAN was initially present in the droplets. Methanol is a nonsooting fuel and as such the initially pure methanol droplets did not display yellow flames. The yellow coloration with the HAN-methanol droplet flames may have been from soot, though further experiments are needed to investigate this possibility. The HAN-methanol mixture droplets generally did not exhibit bubbling while flames were present. However, the flames around these droplets would extinguish prior to complete droplet gasification. The remaining liquid would then bubble intensely (because the igniter was still energized) until all the liquid was gone. The bubbling was likely a result of HAN decomposition in the liquid phase. Initially pure methanol droplets did not bubble at all, which was expected.

Other observations from these experiments are as follows. HAN-glycine droplets displayed luminous flames in air but not in N_2. Also, HAN-glycine droplets left substantial residue behind and did not burn as completely as XM46. The XM46 flames were generally much larger than the HAN-glycine flames (as imaged by the ICCD camera). TEAN-water drops in air go through an evaporation stage followed by diffusion flame combustion of the condensed molten TEAN that remains after the water has evaporated. Finally, it is noted that these normal-gravity experiments clearly showed that buoyant flows were prevalent, e.g., from observations of flame shapes as well as the difficulties in igniting some of the droplets. Ignition difficulties were related to the buoyant flow produced by the igniter, which carried reactive species away from droplets.

REDUCED GRAVITY EXPERIMENTS

The reduced gravity research involves studying combustion characteristics of droplets initially in the mm size range. A drop rig is being constructed for use at the NASA Glenn 2.2 Sec Drop Tower. The design of this drop rig is primarily based upon the droplet combustion test rigs that are presently in use at the NASA Glenn Research Center. However, for these experiments, the pressure vessel has been modified to allow pressures up to 30 atm to be achieved. This vessel is mounted on a drop frame with imaging, electronic and fluid handling systems.

Orthogonal views will be used in these experiments. One view is used to image droplets and the other to image flames. The droplet view, which will be backlit, will utilize a high-speed camera to capture transient droplet behaviors. The flame view will not be backlit, and two cameras will be used to image flames. A 16 mm cine camera (or high-speed video camera) will be used to image visible gas-phase combustion behaviors, and an ICCD camera will be used to image OH emissions. The construction of the vessel is nearly complete. It is expected that microgravity experiments will commence shortly.

THEORETICAL RESEARCH

Theoretical efforts are focused upon providing theory to explain and interpret the results from the normal-gravity and reduced-gravity experiments. For example, it is clearly of interest to develop theory to provide interpretations of unexpected results such as the very large flames of XM46 droplets as well as the yellow coloring observed with the HAN-methanol droplets. The theoretical efforts are essentially divided into two efforts. In the first effort, rational theoretical models (based on existing HAN-based propellant deflagration theory [6] or new models to be developed) will be applied to the HAN-based liquid propellants. Theoretical models that are consistent with the experimental data will be selected or developed. Influences of phenomena such as nonequilibrium vaporization, two-phase flow, gas solubility in liquids, and the presence of a fuel species (e.g., TEAN) will be considered. The second effort is directed towards developing models of TEAN and glycine droplet/residue combustion, where it is evident from the experiments that condensed-phase pyrolysis may need to be accounted for. An emphasis of the theoretical work is to develop analytical models.

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REFERENCES

1. Klein, N., Report ARBRL-02471, Ballistic Research Laboratory (1983).
2. Jankovsky, R. S., AIAA Paper 96-2863.
3. Wucherer, E. J., and Christofferson, S., AIAA Paper 2000-3872.
4. Farshchi, M., Vaezi, V., and Shaw, B. D., paper 223 presented at the 2nd Joint Meeting of the US Sections of the Combustion Institute, Oakland, CA (2001).
5. Beyer, R. A., CPIA Publication 557, Volume I, p. 605 (1990).
6. Shaw, B. D. and Williams, F. A., 24th Symposium (Int'l.) on Combustion, p. 1923 (1992).

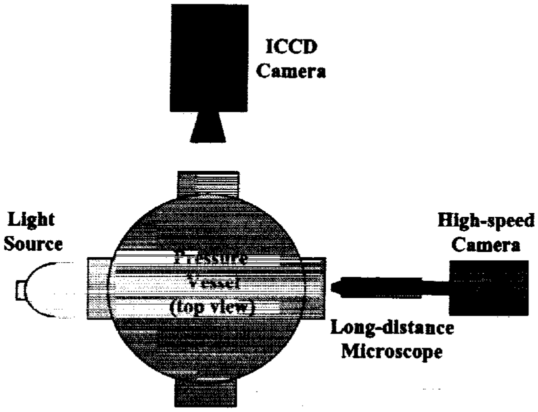

Figure 1. 1-g pressure vessel and cameras.

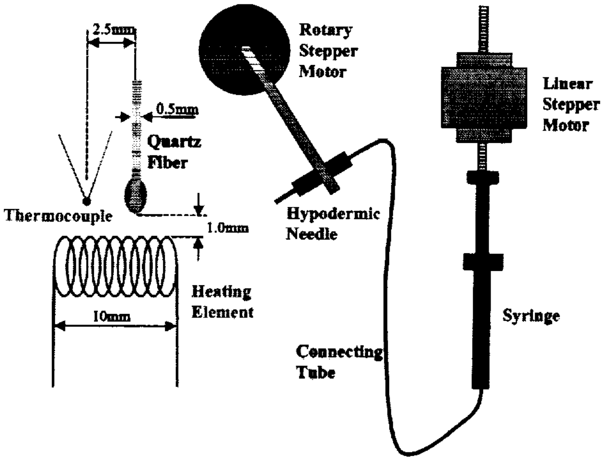

Figure 2. Droplet dispensation and gas temperature measurement systems.

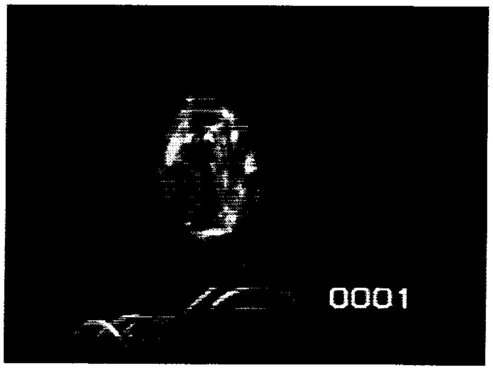

Figure 3. HAN-water droplet in air at 1 atm. Bubbles are present in the droplet.

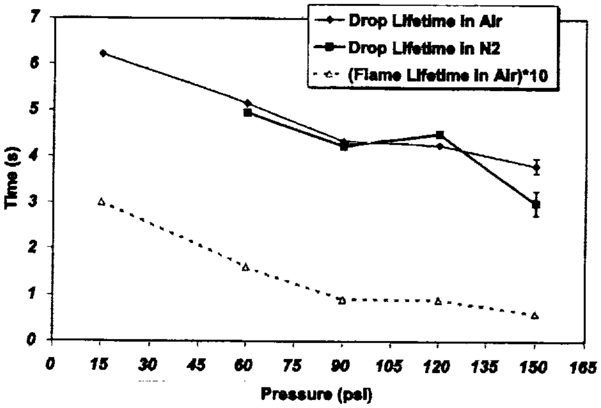

Figure 4. XM46 droplet and flame lifetimes.

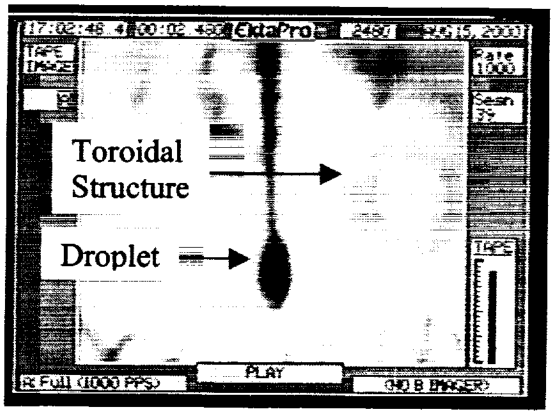

Figure 5. XM46 droplet in N_2 at 60 psi.