vortices generated by lobed mixers are much more effective than ring vortices in providing entrainment and mixing.

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Combustion and Microexplosion of Han-Based Liquid Gun Propellants at Elevated Pressures

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Introduction

PRESENTLY there exists much interest in the use of a class of liquid propellants (LP) for the launching of gun ordnance.[1] These propellants are composed of salts of hydroxylammonium nitrate (HAN) and an aliphatic ammonium nitrate (AAN) dissolved in water. Since HAN is oxygen rich based on N_2–H_2O stoichiometry, whereas AAN is oxygen deficient, they are usually mixed in stoichiometric proportions for maximum propellant energy density. The AAN that is being widely studied at present is triethanolammonium nitrate (TEAN); the specific LP being tested is coded 1845, which consists of 63.2% HAN, 20% TEAN, and 16.8% water, all by weight. This LP has a heating value of about 1 kJ/g and a calculated adiabatic flame temperature of 2285 K. This is the LP adopted for most of the tests conducted in the present study.

Very little is known about the combustion properties of these propellants, although some useful information has been recently reported.[2–4] Specifically, in Ref. 2 it was determined, for atmospheric pressure conditions, that the liquid-phase reaction of LP-1945 is initiated around 200–230°C, that HAN is the component that initiates this reaction, that in practical situations this temperature range can be lower because of the preferential gasification of water and thereby concentration of the salts prior to the onset of reaction, and that there seems to exist a critical salt concentration at which reaction occurs spontaneously. In Ref. 3 data on supported droplets in very high-pressure environments were reported, including observations of droplet microexplosion. In Ref. 4 the flame propagation process within the LP was studied under high-pressure situations, from 68 to 300 atm. The results again demonstrate that it is HAN that initiates the reaction. In Ref. 5 the thermodynamic critical parameters of the LP were estimated. The results show that the critical pressure can be very high such that the LP may not attain criticality during most of the burning time within the ultrahigh pressure environment of the gun chamber.

In the present investigation we extend the droplet combustion work of Ref. 2 to mildly elevated pressure environments. The work is primarily motivated by the recognition that liquid-phase reaction is a crucial element of LP combustion, and that its initiation and intensity can be greatly affected by the liquid temperature. Because thermodynamically the attainable liquid temperature increases with increasing pressure, it is reasonable to expect that the liquid-phase reaction can be correspondingly facilitated by increasing the system pressure. We shall demonstrate subsequently that this concept of pressure-enhancement is indeed viable.

The experimental methodology is presented in the next section, which is followed by discussion of the experimental results.

Experimental Methodology

A steady-flow combustion chamber is used to study the gasification and microexplosion of freely falling LP droplets. A schematic of the apparatus as well as details of the experimentation can be found in Refs. 6 and 7. The experiment involves injecting downward a steady stream of monodisperse and equally spaced LP droplets into the hot postcombustion zone of a flat flame, and observing the subsequent combustion event by freezing the droplet image with stroboscopic backlighting. A solid-state charge-coupled device camera is mounted on a zoom microscope for droplet imaging. The camera signal is transmitted to a video recorder and a high-resolution monitor, allowing a convenient means for focusing and recording. The overall magnification from the actual droplet size to the video monitor is about ×275, and the measurement uncertainty is less than 2% of a typical 200-μm droplet. All of the steady droplet gasification data were taken with a temperature variation of less than 50 K; in most cases the variation is less than 25 K. The gas temperature reported in the following is the thermocouple measured value at about the midpoint in the droplet lifetime. Typical accuracies of experiments of this nature are discussed in Ref. 6.

Results and Discussions

Observationally, there are several qualitative features of HAN-based LP combustion that distinguish it from hydrocarbon fuels. First, hydrocarbon fuels have a thin blue diffusion flame that surrounds the droplet stream. This diffusion flame can also be accompanied by a yellow soot layer that is interior to it. The flame standoff ratio typically ranges from 4 to 10. However, for LP combustion, the droplet stream is completely surrounded by a faint orange glow that extends out up to 40 droplet radii. Thus, in contrast to hydrocarbon fuels, there is no clear distinction between pure vaporization and thin flame burning. The gasification rates of these propellants are low, primarily controlled by that of water, as will be shown later.

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For comparison, a typical hydrocarbon fuel would have a gasification rate 10 times larger.

The propellants microexplode at all pressures tested. The droplets in a stream do not all fragment at precisely the same location. Rather, the event is usually spread out over a range of about 15–30 ms. The change in droplet diameter is small during this period, and the microexplosion diameter is chosen from the upper region of the range.

Photographs of the microexplosion event at atmospheric pressure are shown in Fig. 1a. Each successive frame shows a different droplet at a slightly advanced stage of the nucleation event. Some droplet images contain a bright spot in the center of the droplet caused by the backlighting passing through the droplet center. It is seen that microexplosion is initiated by an expansion of the entire droplet. The extent of expansion indicates that it is caused by internal gasification, whereas the uniformity of expansion before rupturing indicates that the bubbling is initiated away from the surface. This state of expansion continues until the droplet eventually ruptures and the liquid fragments into smaller droplets.

However, this phenomenon of large expansion was not observed for microexplosion at elevated pressures. Figure 1b, obtained at 4 atm, shows that the event is now characterized by mild expansion and then sudden rupturing. A vapor bubble is not apparent in the droplet interior during the event. Shortly after the droplet fragmentation, the small particles are consumed in a bright yellow flash. This secondary microexplosion was observed only above 3 atm. The short delay between the two microexplosion events is estimated to be about 50 ms. Not all microexplosions look similar at a given set of ambient conditions, but these photographs are representative of the common features at the stated pressures.

Quantitatively, the independent system parameters that turned out to be important are the ambient pressure p, ambient temperature T, initial droplet size D_0, and initial water content in the LP. With these parameters specified, we measure the droplet diameter D as a function of time t, especially its value just prior to the state of microexplosion D_{ex}.

Figure 2 is a typical D^2-t plot in accordance with the D^2-law of droplet gasification. It is seen that, after the initial droplet heating period, D^2 varies fairly linearly with time. For higher pressures the data bends down slightly, indicating a gradual increase in the gasification rate. In all cases shown, droplet gasification was terminated in microexplosion.

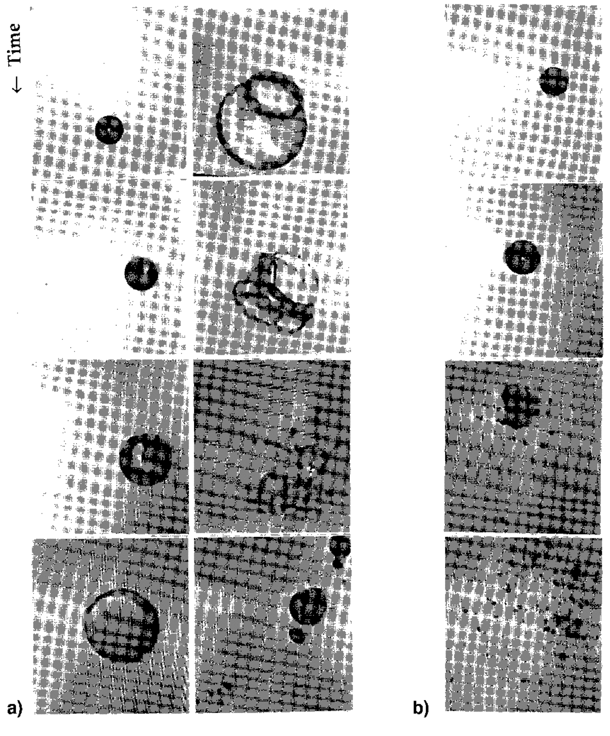

Fig. 1 Typical microexplosion event at a) 1 and b) 4 atm.

From the D^2-t data, a gasification rate constant K can be approximately defined as the negative of the slope of the best-fit straight line passing through the data in the active gasification regime. Figure 3 shows K of LP 1845 as a function of T for $p = 1$ atm and $D_0 = 185$ μm. We first note the very small values of K as compared to the typical values of 0.8–1.0 mm^2/s for hydrocarbon droplet combustion. We next note that the droplet gasification rate increases quite significantly with T. There are two possible causes for such an increase. The first is simply the increase in the heat transfer rate from a hotter surrounding to the droplet. The second is the initiation of some mild liquid-phase reactions within the droplet. Thus, with increasing gas temperature, the rates of these reactions and the associated heat release also increase because of the higher droplet temperature. This then leads to a faster droplet gasification rate.

To distinguish which of these two possibilities is the major contributing factor to the enhanced burning rate, we have also determined the variation of K with T for water only; in this case liquid-phase reaction is absent such that the variation can only be caused by enhanced heat transfer. Figure 3 shows that for pure water K increases only slightly with increasing T, therefore indicating that the sensitive response of the LP droplet to ambient temperature variation is caused by liquid-phase reactions.

The result that mild liquid-phase reactions exist in the droplet interior over an extended period of time, prior to the onset of microexplosion, also agrees with the additional result that K increases with D_0 (Fig. 4a). This is because K should be a constant for a nonreacting droplet undergoing steady gasification in a hot surrounding. Thus, the positive dependence on D_0 is a manifestation of the effects of increased volumetric heat release and longer lifetime (and thereby longer reaction time) associated with larger droplets.

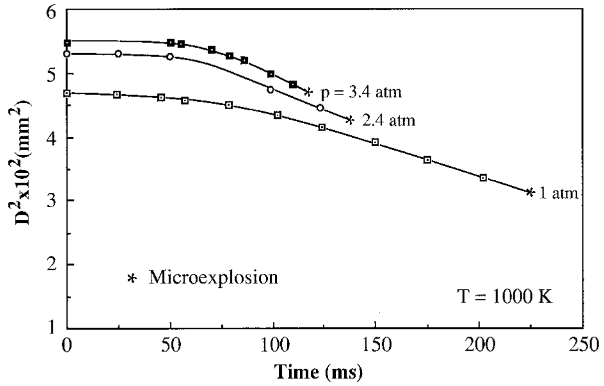

Fig. 2 D^2-t plot for LP 1845 for three different pressures.

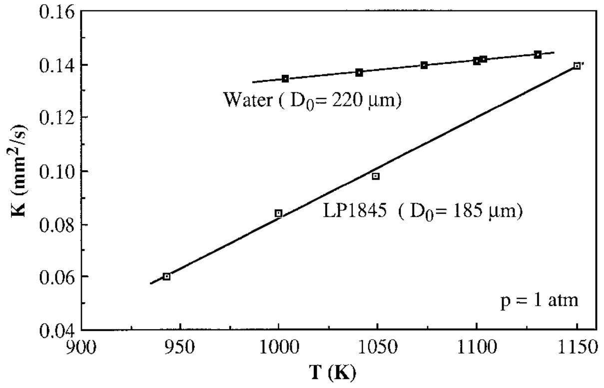

Fig. 3 Gasification rate constant for LP 1845 and water as functions of ambient temperature at 1 atm.

Figure 4b shows the dependence of K on p. It is seen that the dependence is again very strong, with the similar sensitivity as the dependence on T shown in Fig. 3. It is reasonable to suggest that the increase in K is caused by the enhanced liquid-phase reaction because of the increase in the droplet temperature with increasing pressure.

We now present results on droplet microexplosion. The efficiency of microexplosion is quantified by D_{ex}/D_0 such that a value near 1 indicates early microexplosion and thereby a maximum effect on facilitating droplet gasification.

Figure 5 shows that increasing ambient temperature advances the occurrence of microexplosion. This is in agreement with the result implied by Fig. 3 that the droplet temperature increases with T. Thus, with increasing droplet temperature, not only the mild liquid-phase reactions are facilitated to cause a higher K, but the enhanced mild reactions also lead to an earlier attainment of the chemical runaway situation manifested by microexplosion.

Figure 6 shows that for LP 1845, (D_{ex}/D_0) increases with increasing p. This agrees with our earlier anticipation that increasing pressure increases the attainable temperature of the droplet, and consequently advances the state of microexplosion. This advance, however, seems to level off as pressure exceeds 2 atm. Since microexplosions occur almost instantaneously upon gasification ($D_{ex}/D_0 \approx 0.9$), such a leveling off is to be expected because of the finite amount of time needed to heat up the initially cold droplet.

Finally, Fig. 6 also shows that microexplosion is delayed with increasing water content. This is reasonable because more water needs to be depleted from an LP with a higher water content for the salt to be sufficiently concentrated for chemical runaway to take place.

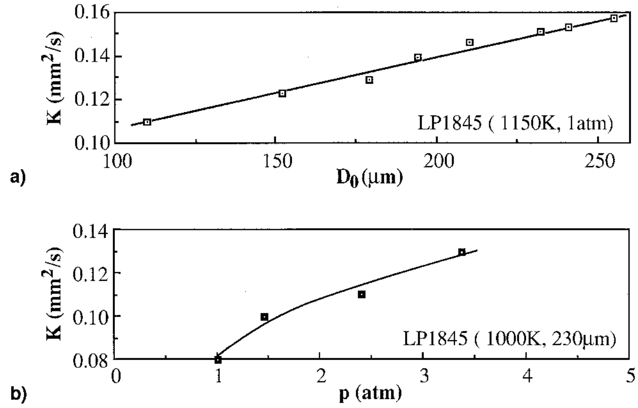

Fig. 4 Gasification rate constant for LP 1845 as functions of a) initial droplet diameter at 1 atm and 1150 K and b) ambient pressure at 1000 K.

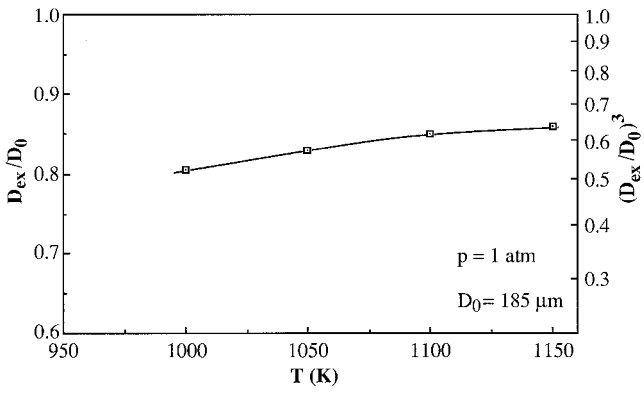

Fig. 5 Microexplosion diameter of LP 1845 as function of ambient temperature at 1 atm.

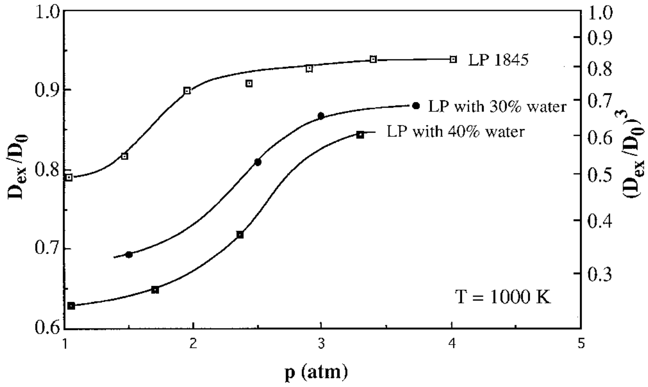

Fig. 6 Microexplosion diameter of LP 1845 with water addition as a function of pressure at 1000 K.

Concluding Remarks

The combustion of freely falling liquid propellant droplets in a high-temperature, mildly elevated-pressure environment up to about 4 atm has been studied. Results demonstrate that the gasification rate of LP droplets sensitively increases with increasing ambient temperature and pressure. The increase is reasoned to be caused by the increase in the droplet temperature, and hence, the liquid-phase exothermic reaction rate. The possibility that such an increase is caused only by the increase in the droplet temperature without liquid-phase reaction is ruled out by the sensitivity of the increase as compared to that for pure water vaporization.

The presence of liquid-phase reaction also leads to the occurrence of droplet microexplosion, which is shown to be also facilitated with increasing ambient temperature because of the corresponding increase in the droplet temperature.

The final point to note is that although the present investigation was conducted at elevated pressures, the maximum attainable pressure here is much too low compared to those relevant for gun propulsion applications. However, the basic concepts identified herein, especially the sensitive dependence of the salt reactions on the temperature of fluid in which it is dissolved, and the preferential gasification of water from the propellant, are expected to be useful.

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