Effect of Oxidizer Concentration on Combustion Instability of a Solid Propellant

D. W. Rice*

U. S. Naval Ordnance Test Station, China Lake, Calif.

Nomenclature

Y = specific acoustic admittance
V_{pg} = velocity of product gases
P = mean chamber pressure
μ/ϵ = response function of combustion zone
L = length of combustion gas column
ρ_g = density of product gases in chamber
c = velocity of sound in combustion gases
α_g = exponential growth rate constant of oscillations
α_d = exponential decay rate of oscillations
ρ = density of solid propellant
r = linear burning rate of solid propellant
f = frequency of oscillations
λ = wavelength of oscillations
γ = ratio of specific heats of gas
ϵ = amplitude of fractional perturbations in pressure
μ = fractional mass perturbation of amplitude μ caused by ϵ
σ = factor dependent upon rate at which ϵ is applied
$\dot{\mathcal{E}}$ = rate of energy release per unit area of propellant
ΔH_{exp} = heat of explosion

Introduction

THE understanding of combustion instability in solid rocket motors has grown considerably in the past decade. The complexity of the problem has been such that theoretical models apply only to certain portions of the broad spectra of unstable behavior.

Combustion instability can be divided into two broad areas. First, the energy source or propellant and second, the energy sinks such as bulk losses and losses through the nozzle. The focus of this report is on the energy source. The effects of varying certain physiochemical properties of a solid propellant on its oscillatory behavior have been previously reported. Variance in the oxidizer particle size and burning-rate modifier were shown to cause large changes in a propellant's oscillatory behavior, whereas changes in fuel composition exhibited small effects.[1] The purpose of the following study was to examine what effect the oxidizer-fuel ratio had on the oscillatory characteristics of an ammonium perchlorate-polybutyl acrylic acid terpolymer (PBAA) composite propellant.

Theory

The ability of a propellant to drive oscillations in an end-burning motor can be characterized by the real part of the specific acoustic admittance of the burning surface[2]:

$$Y = (V_{pg}/P)\ [(\mu/\epsilon) - \sigma] \tag{1}$$

When the admittance is positive, pressure disturbance incident on the propellant surface will be attenuated, wheraes negative values imply amplification.

If we focus our attention on a double-end-burning motor where pressure oscillations grow and decay in an approximately exponential manner and neglect mean gas flow, Strittmater[3] showed that the admittance could be given by

$$Y = -\ (L/2\rho_g c^2)\ (\alpha_g - \alpha_d) \tag{2}$$

Furthermore, if we limit ourselves to first mode oscillations ($\lambda = 2L$), combination of Eqs. (1) and (2) with the expression $2Lf = c$ and $V_{pg}\rho_g = r\rho_s$ gives

$$(\mu/\epsilon) - \sigma = (P/4c\rho_s r)\ [(\alpha_g - \alpha_d)/f] \tag{3}$$

Neglecting mean flow in the foregoing relationship may lead to large errors in the specific acoustic admittance. By inclusion of mean flow, for small values of the admittance, McClure, et al.[4] showed that

$$\mu/\epsilon = (P/4c\rho_s r)\ [(\alpha_g - \alpha_d)/f] \tag{4}$$

and[5] $\sigma \simeq 1/\gamma$. We note from these results that, when $\mu/\epsilon > 1/\gamma$, the admittance will be negative and pressure disturbances will be amplified at the propellant surface.

Experiment

A 1.5-in.-diameter double-end-burning motor was used to evaluate the response function[6] of a composite ammonium perchlorate-PBAA propellant with different oxidizer-fuel ratios (Table 1). The response function was measured from 500 to 5000 cps at a pressure of 200 psig for each propellant (Fig. 1) except in the cases where the marginal oscillatory behavior of the propellant limited the frequency range. The pressure was held constant by firing into a surge tank through a subsonic nozzle. The frequency was determined by the motor length. Primarily, first-mode pressure oscillations were observed; therefore, Eq. (4) could be used to evaluate the response function. The detailed experimental techniques used in firing the motors and analyzing the data were similar to those outlined by Horton and Rice.[1]

The three propellants with oxidizer concentration above 80% could not be prepared by normal mixing-casting procedures, but had to be pressed to the desired size. The ammonium perchlorate and PBAA were mixed for 6 hr, after which time microscopic examinations showed that the oxidizer was coated with fuel. The polymerizing catalyst Epon 828 was then added and mixing continued for 1 hr. Thirty grams of this mixture were placed in a 1.5-in.-diam brass die and pressed at 40,000 psig. These propellant disks were allowed to cure at 160°F for five days.

A small number of disks were pressed with an oxidizer concentration of 76% and the response function compared to that of a mixed propellant with a similar oxidizer concentration. There was no observable difference in the response functions, showing that the pressing, per se, had negligible effects on the response function.

Discussion

The experimental results indicate that the response function is only slightly affected by the oxidizer-fuel ratio. As can be seen in Fig. 1, the propellant with the lowest oxidizer concentration was the most unstable, i.e., had the largest

Table 1 Propellant compositions and experimental constants for various ammonium-perchlorate-PBAA propellants

Propellant designation	Wt %, NH_4ClO_4, 80μ	Wt %, PBAA	Burning rate, in./sec, 200 psig	ρ_s, lb/in.^{3}	$\Delta H_{exp} \times 10^{-3}$, cal/lb	c, in./sec
A-13	76	24	0.164	0.0570	453	35,000
A-27	85	15	0.282	0.0600	616	37,200
A-28	90	10	0.242	0.0614	674	36,600
A-29	95	5	0.173	0.0630	647	...

Received April 24, 1964.

* Chemist, Aerothermocehmistry Group.

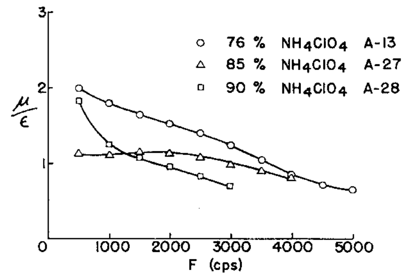

Fig. 1 Comparison of response function-frequency curves for three composite propellants differing only in oxidizer concentration.

response function. The highest oxidizer concentration examined oscillated in the end burner, but with such small amplitudes that growth and decay constants could not be measured. An estimate of the response function would be 0.3 to 0.6 between 500 and 2000 cps, whereas above 2000 cps, the value would be less.

We might speculate that the relative instability of these propellants is proportional to the rate of energy release in the total combustion zone (product of heat of explosion, linear burning rate, and density). Figure 2, which is a plot of energy release in the combustion zone ($\dot{\mathcal{E}}$) as a function of oxidizer concentration at 200 psig, shows that, based on this speculation, the propellant with 85% oxidizer should be the most unstable. Because this is not consistent with the experimental results, the speculation must be considered inadequate.

If we concentrate on more detailed aspects of the combustion, we find that the energy release in the diffusion flame zone may very well explain the results, i.e., the rate of energy release in the diffusion flame zone may be a maximum at a lower oxidizer concentration than the rate in the combustion zone as a whole, causing the 76% oxidizer system to be most unstable. This speculation implies that the diffusion flame is the responsive mechanism to pressure disturbances. This seems likely in that, of the two major energy release mechanisms, diffusion flame and oxidizer decomposition, the oxidizer decomposition has a rapid response in terms of the period of oscillation in the frequency region below about 4000 cps. Above 4000 cps, the ammonium perchlorate decomposition flame may begin to play a role in the combustion response and at higher frequencies may be the dominant response mechanism. This speculation will be examined both analytically and experimentally in the future.

Summary

The oxidizer-fuel ratio has only subtle effects on the unstable behavior of a solid composite propellant as compared to the effects of oxidizer particle size and burning-rate modifier. These subtle effects may eventually be explained in terms of the energy release in the diffusion flame zone, but to date this is only speculation.

References

[1] Horton, M. D. and Rice, D. W., "The effect of compositional variables upon oscillatory combustion of solid rocket propellants," Combust. Flame **8**, 21–28 (March 1964).

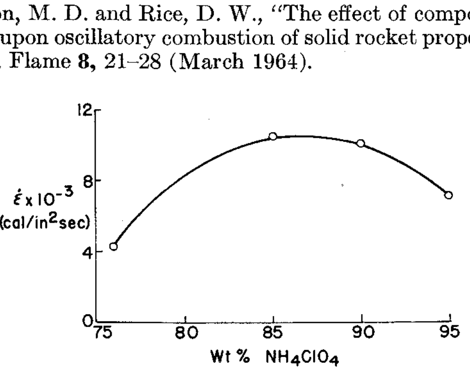

Fig. 2 Energy release in the combustion zone ($\dot{\mathcal{E}}$) at 200 psig as a function of weight percent ammonium perchlorate.

[2] Hart, R. W. and McClure, F. T., "Combustion instability: acoustic interaction with a burning propellant surface," J. Chem. Phys. **30**, 1501–1514 (1959).

[3] Strittmater, R., Watermeier, L., and Pfaff, S., "Virtual specific acoustic admittance measurements of burning solid propellant surfaces by a resonant tube technique," *Ninth Symposium (International) on Combustion* (Academic Press, New York, 1963), pp. 311–315.

[4] McClure, F. T., Hart, R. W., and Cantrell, R. H., "Interaction between sound and flow stability of T-burners," The Johns Hopkins Univ., Applied Physics Lab., Rept. TG 335-12 (July 1962).

[5] Hart, R. W. and Cantrell, R. H., "Amplification and attenuation of sound by burning propellants," The Johns Hopkins Univ., Applied Physics Lab., Rept. TG 335-11 (July 1962).

[6] Horton, M. D., "One dimensional solid propellant oscillatory burner," ARS J. **31**, 1596 (1961).

Structure of the Boundary Layer at the Leading Edge of a Flat Plate in Hypersonic Slip Flow

J. A. LAURMANN*
Lockheed Missile and Space Laboratories, Palo Alto, Calif.

IN an unpublished report[1] we have presented a solution for viscous hypersonic flow over a flat plate according to the linearized Oseen equations. The analysis was made with the thought that the linearized model might provide a valuable approximation to an otherwise intractable problem as well as serving as a guide to methods of treating the full nonlinear equations. Since the primary objective was the study of the nature of the boundary-layer/inviscid-flow interaction process all the way to the leading edge, rarefaction effects in the form of velocity slip and temperature-jump boundary conditions were an essential ingredient in the calculations. The solution showed that in the hypersonic limit the effect of these modified boundary conditions was quite radical, resulting in a flow at the leading edge which was unperturbed from the freestream state: there was "perfect slip" at the leading edge. This result means, of course, that the linearized equations should depict correctly the initial departures from freestream conditions at the leading edge. In view of the importance of this result in the wider context of the complete nonlinear formulation, it would seem to be worthwhile to present here the essence of the method used and some of the other conclusions reached. Full details are available in Ref. 1.

Method of Solution

In brief, the linearized compressible Oseen equations are represented in nondimensional form using the mean free path $\lambda \propto Re/M$ as the scaling length; here Re is the freestream Reynolds number per unit length and M the Mach number. A boundary-layer type of behavior is assumed, rates of change in the x direction along the plate being taken of order $1/M$, $M \to \infty$ compared with rates of change in the y direction normal to the plate. The Lagerstrom-Cole-Trilling method[2–4] of splitting the Oseen equations into longitudinal and transverse waves is employed, and, in the hypersonic limit $M \to \infty$, these reduce to

Pressure Wave (longitudinal)

$$\frac{\partial^2 \varphi_l}{\partial \xi^2} - \frac{\partial^2 \varphi_l}{\partial Y^2} = \beta\gamma \frac{\partial^3 \varphi_l}{\partial \xi \partial Y^2} \qquad \mathbf{q}_l = \nabla \varphi_l \tag{1}$$

Received May 7, 1964.

* Staff Scientist; now at the Defense Research Corporation, Santa Barbara, Calif. Member AIAA.