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Leading-Edge Flame Detachment: Effect on Pressure-Coupled Combustion Response

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An experiment was conducted to establish the critical role of a detailed aspect of the flamelet structure in composite propellants in determining the overall combustion response to pressure oscillations during combustor instability.

Nomenclature

a_b = velocity of sound of gases in T-burner
g_c = units conversion factor
L = length of interior cavity of T-burner
R_p = pressure-coupled response function
r = burning rate
S_b = cross-sectional area of cavity of T-burner
S_c = burning surface area of propellant sample
$\boldsymbol{\alpha}_c$ = combustion amplification
α_d = burner damping during burning
α_1 = exponential growth rate during burning, decay rate in pulse test
α_2 = decay rate after burnout
$\alpha_2(t_1)$ = decay rate corrected to frequency during burning
$\boldsymbol{\rho}_s$ = density of solid propellant

Introduction

THE pressure-coupled response of combustion rate to imposed pressure disturbances is the primary cause of combustion instability in solid rocket motors. This response has been difficult to measure reliably and to model analytically. There is not yet an analytical model that describes the physical phenomenon realistically for heterogeneous propellants. This paper concerns an experiment designed to illustrate the importance of a basic aspect of the flame response that is absent or superficially represented in current models, but that is expected to be important.

To describe this aspect of flame response, it is necessary to describe certain microscopic aspects of the flame complex (described in some detail in Refs. 1–3). The burning surface of a typical heterogeneous propellant consists of areas of burning oxidizer, ammonium perchlorate (AP), interposed in a connected web of hydrocarbon polymer binder that holds the matrix together and supplies the fuel for the oxidizer/fuel (O/F) diffusion flamelets around the AP particles. Those flamelets (Fig. 1) provide the primary source of heat for the pyrolysis of the fuel. The character of a diffusion flamelet is illustrated in Fig. 2. As the nominally parallel flows of oxidizer and binder vapors move outward from the surface, a diffusion layer develops, with a progressively increased O/F mixture as a function of distance outward. Interior to this mixing fan is a stoichiometric surface, which is typically thought of as the site of the diffusion flame. The onset of this flame is located somewhere far enough from the surface for a balance to be maintained between the local heat release and the heat lost to the surface and oncoming flow. At that point, e.g., 50 μm or so from the surface at 3.5 MPa, there is enough flammable mixture to result in an intense sustainable heat release, referred to here as the leading-edge flame (LEF) for the outer diffusion flame. Such a flamelet has been referred to variously as a flame root,[4] a phalanx frame,[5] and a primary flame.[6] The actual location and scope of the LEF are determined by the kinetics of the O/F reaction and by the diffusion process that prepares the mixture upstream of the LEF. As such, the energy of the LEF and its proximity to the surface are dependent on pressure. Further, the heat release may be relatively large because the LEF burns a substantial amount of premixed oxidizer and fuel close to the surface. Thus, the LEF can be a relatively large contributor to the local surface heating along the O/F contact line in the oxidizer–binder surface. Because of its proximity to the heterogeneous surface, the characterization of the individual LEF must be regarded as a three-dimensional process, localized above the outer boundary of the oxidizer particle surface with three-dimensional heat return to the surface. It is important to note that the close three-dimensional coupling between the LEF and the O/F contact line makes it impractical to represent the dynamic response of the combustion by any conventional one-dimensional, surface-averaged model. Put more generally, whereas the combustion response that is important to the combustor instability is a surface-averaged response, this response is determined primarily by the responses of a myriad of microscopically nonsteady, three-dimensional localized processes in the combustion layer.

The present research is based on the postulate that when the LEF retreats from the surface with decreasing pressure it will arrive at the stoichiometric tip (Fig. 3) at some specific pressure (dependent on the size of the AP surface); and upon a further decrease in pressure, the LEF will be quenched, and the O/F flame for that particle will establish itself at some more remote location typical of a fuel-rich premixed flame. In practice, this discontinuous jump in the flame cannot be observed directly because 1) in a practical (rocket-motor-like) environment, the event is too small to be spatially resolved experimentally; and 2) the details of the event depend on the state of neighboring flamelets from AP surfaces of different sizes (from either different sizes of AP particles or different stages in the burning of like particles).

If one could make a propellant consisting of equal-size parallel rods of oxidizer, and burn it endwise with progressively lower pressure, there would presumably be a collective transition from LEF-dominated burning to premixed-flame burning when pressure reached the LEF detachment level. At that point, an observable drop in burning rate would occur. When particulate oxidizer is used, even with uniform particle size, the size of exposed oxidizer surfaces depends on the burning

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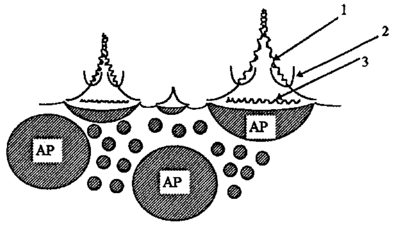

Fig. 1 **Microscopic features of the combustion zone of an AP/hydrocarbon binder propellant (typical of 6–8 MPa). 1, diffusion-limited O/F flame; 2, O/F LEF, holds diffusion flame; and 3, AP self-deflagration flame.**

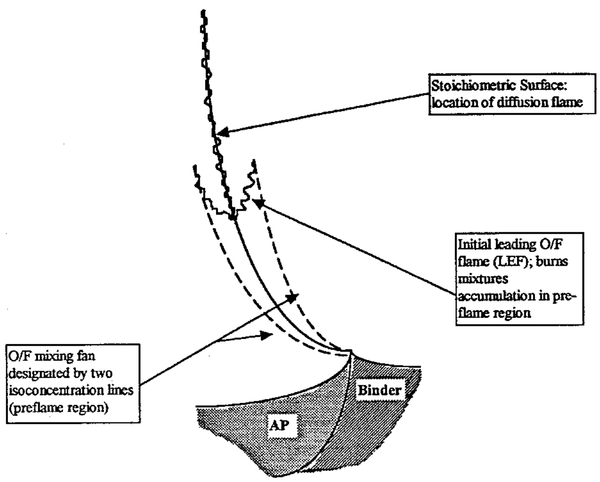

Fig. 2 **O/F mixing fan and diffusion flamelets.**

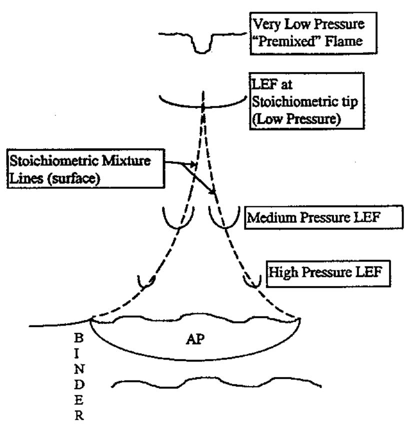

Fig. 3 **Outward displacement of the LEF at decreasing pressure, and the singularity when the LEF reaches the stoichiometric tip.**

stage of the particles. Thus, the burning rate transition associated with LEF detachment would not be abrupt, as in the case of a rod propellant, but it might be manifested over a narrower pressure range than with a propellant with a wide blend of oxidizer particle sizes. This idea was tested as a way of verifying the presence of an LEF-detachment effect on burning rate.[2] The result (Fig. 4) shows a characteristic, particle-size-dependent pressure range in which the burning rate drops off rapidly with decreasing pressure, supporting the postulate of the LEF-detachment effect on burning rate. In Ref. 2 and Fig. 4, the propellant that was used had a bimodal oxidizer particle size distribution to obtain the high O/F ratio typical of commercial propellants. Such a bimodal propellant burns with a surface consisting of scattered large (400 μm) particles and a surrounding fuel-rich matrix of fine AP particles and hydrocarbon binder. The fine component of AP (in the present study) was chosen to have a narrow size distribution. The LEF-detachment effect involves the fine-particle matrix (at intended test conditions).

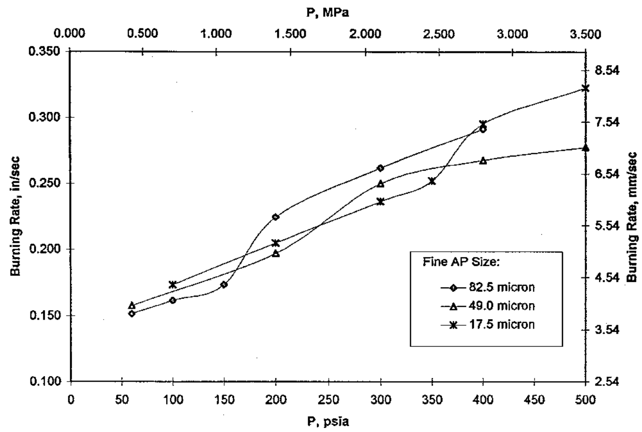

Fig. 4 **Burning rate curves of three bimodal propellants,[2] showing the steep-slope regimes corresponding to LEFs at transition condition (AP–polybutadiene acrylonitrile propellant, 87.5% AP, 8:2 ratio of 400 μm, and indicated fine AP).**

This study is a test of a postulate that, at the LEF detachment (transition pressure ranges), the LEF will periodically detach and reattach if the pressure oscillates, with the reasonable projection that the dynamic combustion–response function will exhibit a maximum at the corresponding transition pressure interval. This effect on pressure dependence of the response function was tested by a series of T-burner tests on a bimodal AP propellant similar to that used in Ref. 2 for Fig. 4.[3,7,8]

Experiment

Strategy

The initial plan was to prepare three propellants similar to those that led to Fig. 4 and use them to run T-burner tests over the pressure range of those earlier burning rate tests,[3] to determine whether a maximum in the response function (Fig. 5) occurred in the pressure intervals in which the rapid rises in mean burning rate were manifested in Fig. 4. Such a result would be consistent with the interpretation that the pressure-coupled combustion response is sensitive to the condition of LEF detachment. (In Fig. 5 the values of R_p were chosen for convenience; the argument requires only that a maximum occur at the indicated pressures.)

In choosing T-burner tests a choice had to be made as to the frequency of the pressure oscillation, i.e., length of the T-burner. It was presumed that the event of LEF detachment and reattachment during a cycle of pressure oscillation involved no slow processes, in which case the effect of LEF detachment–reattachment on the response would not be strongly dependent on frequency. However, this point was tested by choosing three frequencies, 350, 500, and 800 Hz, that would be near that for the maximum response for typical AP propellants of this burning rate.

Practical considerations caused some deviations in the preceding strategy:

1) Cost limited the number of tests, so that testing of the full range of propellants (three) at all three frequencies proposed was not done (Table 1).

2) Propellant processing problems caused a lower coarse-to-fine AP ratio value than that used for the tests leading to Fig. 4.

3) The initial spread of particle size distribution for the fine AP was larger than intended, sometimes resulting in indecisive T-burner test results, i.e., maxima in the measured R_p vs p curves were not as clearly manifested above the scatter in the T-burner test results as implied in Fig. 5. One extra mix of propellant (mix 1b) was made with a relatively more narrow

Table 1 Propellant information

Ingredient	Percent by mass (volume)
Ammonium perchlorate	87.5 (79.4)
Coarse	61.25 (55.58)
Fine	26.25 (23.82)
Binder	12.5 (20.6)
Prepolymer, polybutadiene acrylonitrile acrylic acid (PBAN) (HB polymer)	8.02
Curative, epoxy curing agent (ECA)	2.61
Plastisizer, dioctyl adipate (DOA)	1.88

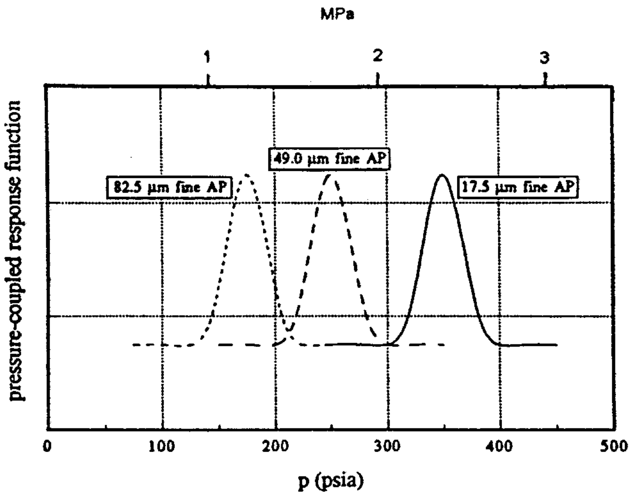

Fig. 5 Expected pressure dependence of the oscillatory combustion response to pressure oscillations for three bimodal propellants (peaks are expected in the pressure ranges of LEF transitions on the fine AP).

size distribution of the fine AP when tests on the 1a mix gave some ambiguous test results.

4) For this family of propellants the T-burners were marginally unstable. Measurements of combustion response were made from spontaneous oscillations when possible; however, there were conditions where spontaneous oscillations did not occur and repeat tests were run with pulsed oscillations.[7,8]

Propellant

Following the lead of Ref. 2 the propellant formulation was chosen to be as shown in Table 1. All mixes used coarse (400 μm) AP with fine AP in a 70:30 ratio. Mix 1a used 17.5-μm-fine AP with a size range of 5.7–53.7 μm (see Ref. 3 for quantitative size distribution). Mix 1b used 19.1-μm-fine AP with a size range of 6.1–36.9 μm. Mix 2 used 43.5-μm-fine AP with a size range of 10–70.1 μm. Mix 3 used 81-μm-fine AP with a size range of 36–120 μm. The propellants were mixed in a 1-gal vacuum mixer and vacuum cast in tubes (somewhat larger in diameter than that of the o.d. for test samples), which were machined to disks of the desired thickness and diameter.[8]

Burning rate vs pressure was determined (Fig. 6) for each mix by video photography of strands burning in a nitrogen-flushed window bomb. It was noted that the r vs p curves did not exhibit the high-slope regions that were identified previously with LEF attachment (Fig. 4). Also, the burning rates were much lower than those in Ref. 2. These large differences from the results with analogous propellants in Ref. 2 were not expected on the basis of the differences in the AP coarse-to-fine ratios (7:3 here, 8:2 in Ref. 2). However, the constraints on the program did not permit further experimentation with the propellant formulation. It was anticipated that the detachment and reattachment of LEFs would be more organized with

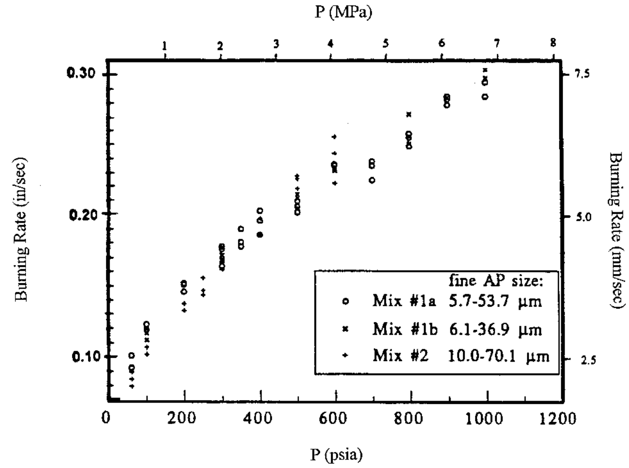

Fig. 6 Burning rate vs pressure for mixes used in this study (for details see Ref. 3).

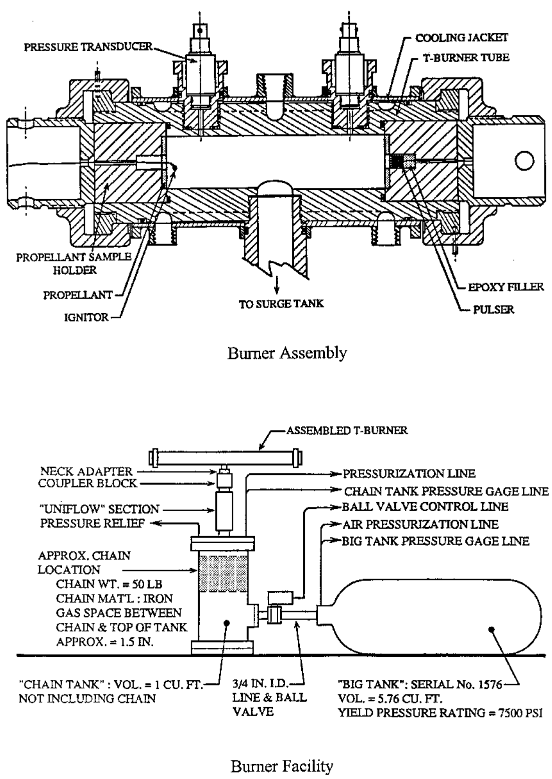

Fig. 7 T-burner test apparatus used in this study.

pressure oscillations than with steady pressure. On this basis, it was judged that the T-burner test program would show the enhanced oscillatory combustion response indicative of coupled LEF response, and so the proposed tests were carried out.

T-Burner

The tests (constant mean pressure) were run in the standard apparatus at the U.S. Naval Air Weapons Center, described in Ref. 8 and in Fig. 7. In this facility the exponential growth rate α_1 of oscillations (or the decay rate of pulses) during burning is computed from the digitized output of the pressure transducer, using a computer code developed at the U.S. Naval Air Weapons Center for this determination. The decay rate α_2 of oscillations (spontaneous or pulsed) after propellant burnout is also measured. The cause of α_1 is the concurrent contribution of α_c and α_d during burning; α_2 is an indication of the damping present during pulse 1, so that the amplification from com-

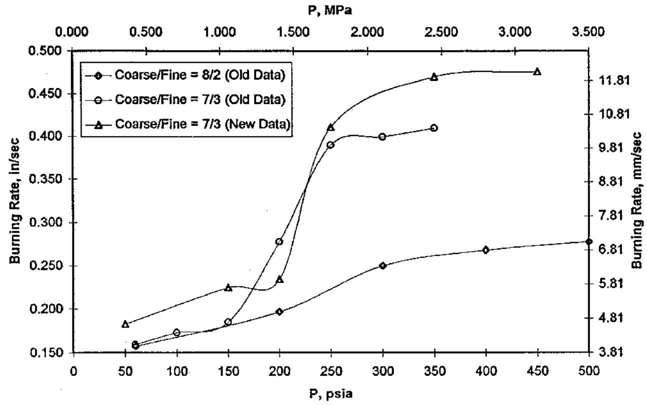

Fig. 8 Burning rates, not previously reported, of propellants analogous to mix 1b, but showing the LEF transition effect reported in Ref. 2 and Fig. 4.

bustion is $\alpha_1 + \alpha_2$. However, a correction to α_2 is usually made because the observed frequency during α_2 is usually lower than during α_1.[8] A dependence of α_2 on frequency is determined from accumulated tests, and an adjusted value of α_2 is used in each test to give α_d corresponding to the measured frequency during α_1

$$\alpha_c = \alpha_1 - \alpha_2(f_1) = \alpha_1 - \alpha_d$$

The in-phase (real) part of the pressure-coupled combustion response is then computed from

$$R_p = \frac{\bar{p} L g_c \alpha_c}{24 \boldsymbol{\rho}_s \bar{r} a_b^2 (S_b/S_c)}$$

This expression arises from the one-dimensional stability analysis for the first axial mode of the T-burner.[8,9]

As noted in the preceding text, some tests exhibited spontaneous oscillatory behavior. This is indicative of high α_c and

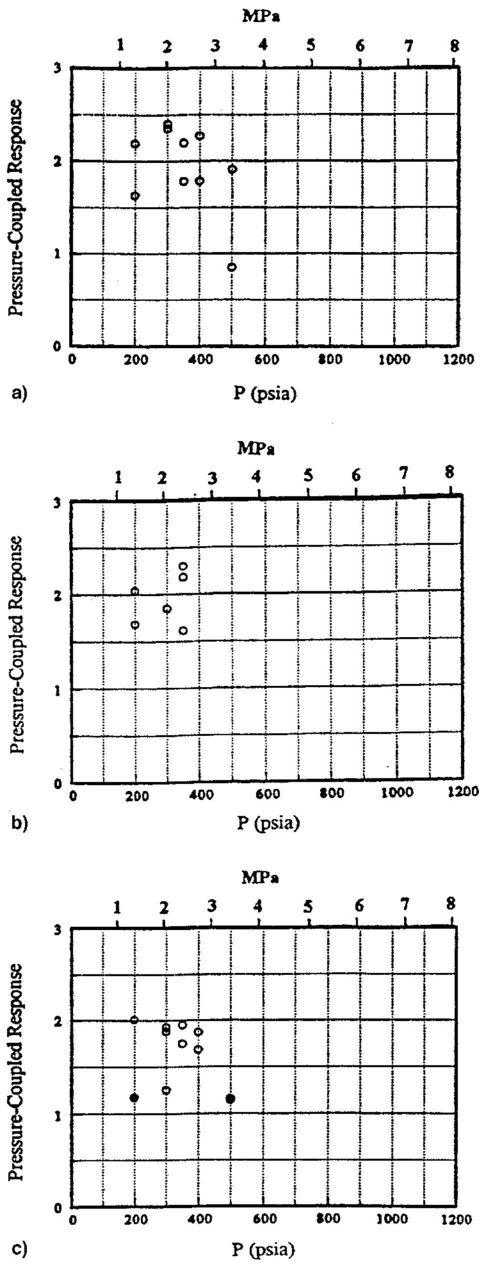

Fig. 9 Response function vs pressure for mix 1a at a) 350, b) 500, and c) 800 Hz. ○ = spontaneous, ● = nonspontaneous.

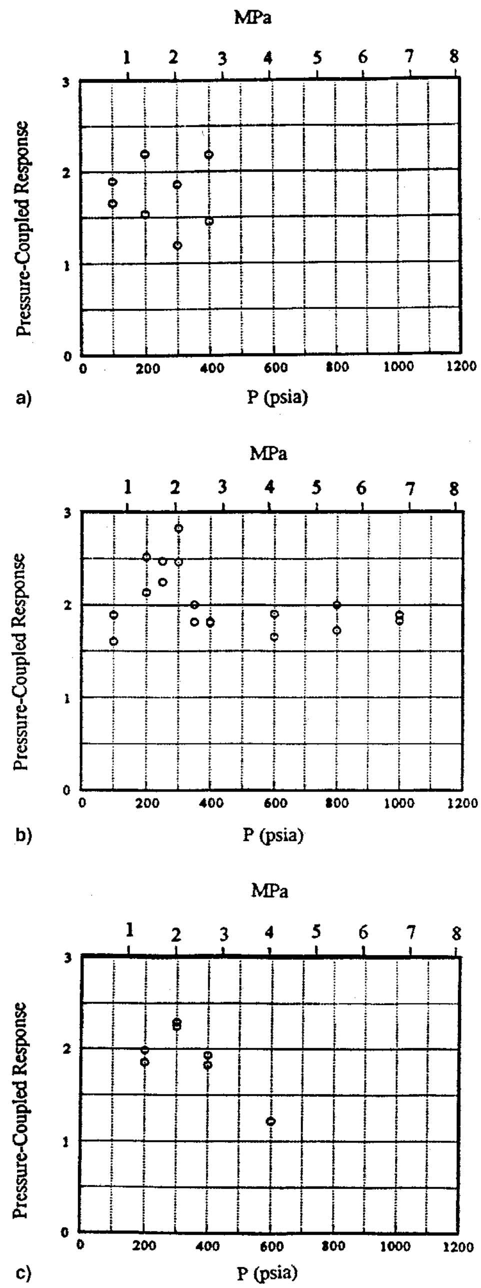

Fig. 10 Response function vs pressure for mix 1b at a) 350, b) 500, and c) 800 Hz. ○ = spontaneous.

R_p under those test conditions, and it generally occurred under test conditions that were expected to (and did) yield high R_p, i.e., propellant mix 1b, and tests with other mixes in the pressure range of postulated LEF detachment instability.

Under some conditions the burners did not oscillate spontaneously, and α_1 and α_2 were determined by the pulsed method.[7,8] This method was required under two different test conditions:

Condition 1: Conduct some tests at pressures above and below the expected LEF transition range.

Condition 2: Repeat tests in a second year on mix 1a at 500 Hz and mix 2 at 800 Hz, i.e., with aged propellants.

The computed values of R_p were low in all of the pulse tests, consistent with the fact that spontaneous oscillations did not occur. Condition 1 is consistent with expected low values of R_p. Condition 2 indicates that the aged propellants behaved differently than they did in first-year tests. (The results of the test on the aged propellants were so different that they were excluded, but are available in Ref. 3 for the record. Discussion with U.S. Naval Air Warfare Center personnel indicated that divergent performance of aged propellants is not unprecedented, but generally unexplained).

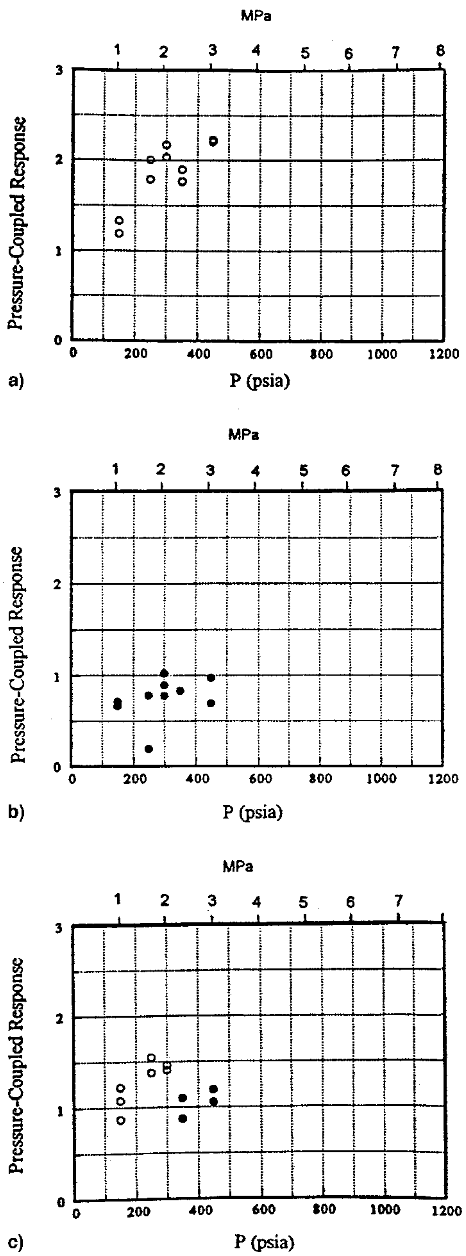

Fig. 11 Response function vs pressure for mix 2 at a) 350, b) 500, and c) 800 Hz. ○ = spontaneous, ● = nonspontaneous.

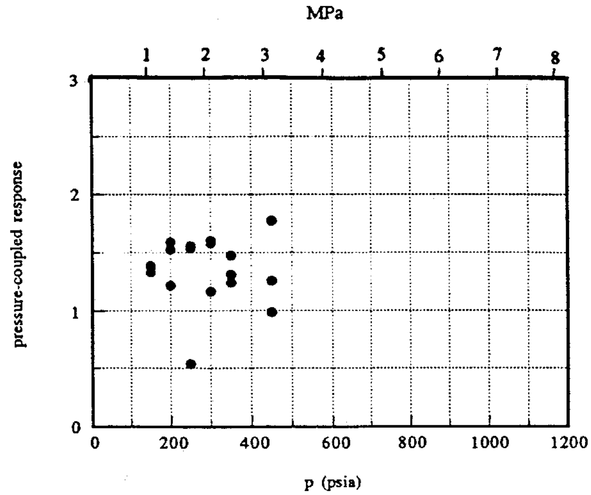

Fig. 12 Response function vs pressure for mix 3 at 500 Hz. ● = nonspontaneous.

Summary of Results

As noted earlier the burning rate vs pressure curves for the present propellants (Fig. 6) did not show the transitions that were reported in Ref. 2 and Fig. 4. This difference was initially attributed to the difference in ratio of coarse-to-fine AP in the propellants. However, a later review of the work leading to Ref. 2 revealed that a 7:3 formulation had been tested then (Fig. 8). The tests of that earlier investigation have recently been repeated and the results are similar to the early study and to Fig. 2 (the new results for the 7:3 formulation are included in Fig. 8). The low rate and absence of transitions in the $r(p)$ curves for the mixes used in the T-burner tests remain unexplained.

The results of the T-burner tests are shown in Figs. 9–12 and are described in the following text.

Mix 1a: Tests were spontaneously unstable in the pressure range expected for LEF transition. Maxima appear to be indicated, but data scatter is bad and measurements at higher and lower pressure are minimal.

Mix 1b: All tests were spontaneously unstable. At 500 and 800 Hz, R_p indicates a clear peak (~2.4 compared to about 1.7 outside an LEF transition pressure range centered on 2.3 MPa. At 350 Hz, the data were too scattered to identify a maximum.

Mix 2: At 350 Hz, all tests were spontaneously unstable and a maximum of about 2.2 is indicated at 2.3–2.8 MPa. Measurements on the high-pressure side of the maximum are lacking. At 500 Hz, all tests required pulsing, resulting in low values of R_p (around 0.8) with no sign of a maximum. At 800 Hz a modest peak in R_p (1.5) is indicated at 1.9 MPa.

Mix 3: This mix was tested only at 500 Hz. All pressures required pulsing, giving an R_p around 1.4, with large data scatter and no systematic pressure dependence.

Taken collectively, the T-burner results show relatively high values of R_p in the postulated LEF transition range of pressure, and lower R_p at higher and lower pressure. Tests under some conditions gave unambiguous evidence of R_p maxima in the LEF transition range. Such results were not extensive enough to establish the postulated dependence of pressure for $(R_p)_{max}$ on the size of the fine AP particles. There were some test sets, notably mix 3 at 500 Hz and mix 1b at 350 Hz, for which the expected R_p maxima were either absent or lost in the data scatter.

Discussion

With all of the adversities of the reported results (anomalous steady-state burning, change in behavior with propellant aging, and failure to show the expected elevated R_p under some test conditions), it could easily be concluded that the results do not demonstrate LEF transition enhancement of oscillatory combustion response. Certainly it would be desirable to repeat the T-burner tests with propellants that showed LEF transition effects in the steady-state burning rate (and to know why mixes 1a, 1b, 2, and 3 did not show such behavior in steady-state burning). However, there is no doubt that these mixes had bimodal oxidizer size distributions that would be conducive to organized LEF transition behavior, and such behavior is evident in much of the response function data (most clearly in Fig. 9b) and at the expected LEF transition pressures. Such selective behavior is unprecedented in tests on conventional propellants, and demonstrates, in accordance with the strategy for the investigation, that oscillatory LEF transition is strongly pressure coupled, so much so that it was manifested even for bimodal propellants that did not exhibit organized LEF transition in the steady-state burning rate. Such a demonstration of the role of any detailed aspect of the flame complex in determining combustion response is unprecedented. However, this is just a beginning as far as LEF transition effects are concerned because LEF transition is a very complex dynamic event about which very little is known. The present results simply demonstrate that it is an important contributor to pressure-coupled response. This is presumably true also for more conventional particle-size distribution, but, because the effect is spread out over the whole pressure range, it is not distinguishable from other aspects of flame complex response. In the interest of more realistic modeling of pressure-coupled combustion response, it will be important to learn more about the dynamics of LEF detachment and reattachment, and of other microscopic, three-dimensional nonsteady behavior in the combustion zone.

Acknowledgments

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