Use of the One-Dimensional T-Burner to Study Oscillatory Combustion

M D HORTON*
U S Naval Ordnance Test Station, China Lake, Calif

This paper desci ibes a simple bui ner used foi the study of oscillatoi y combustion and the iesults obtained therefrom. The burner, commonly called the T-burner, consists of side-vented cylindrical steel chamber in the ends of which pi opellant disks are burned If the propellant combustion spontaneously geneiates piessure oscillations, use is made of the over-all one-dimensional acoustic behavior in the system to characteiize the transient combustion of the piopellant The important vaiiables used in the chaiacterization are the growth iate of the oscillations and their decay rate following the consumption of the piopellant A desciiption is given of the several types of investigations in which the T-bui nei is the primaiy research tool These investigations concern the response function of the combustion zone, the effect of normal pressui e pei tuibations upon the average burning rate of the propellant, the participation of the piopellant in the acoustic motion of the system, the mechanism by which aluminum supiesses oscillatoiy combustion, and the influence of piopellant composition upon the iesponse function of the combustion zone The latter two desciiptions are given in some detail

Nomenclature

c = speed of sound in the combustion gas
f = frequency of the oscillations
l = length of the gas column in the T-burner
n_D = number of particles per unit volume of combustion gas with diameter D
p_m = amplitude of the pressure oscillations
p_0 = amplitude of the pressure oscillations at an arbitrary zero time
p = mean chamber pressure
r = burning rate of the propellant
R = radius of the particle in the combustion gas
t = time
V = speed with which the gas leaves the combustion zone
Y = real part of the specific acoustic admittance of the combustion zone
Z = $(2\pi f R^2/2\nu)^{1/2}$
α_g = exponential constant that describes the growth of the oscillations
α_d = exponential constant that describes the decay of the oscillations
α_a = reduction in α_g which is caused by the presence of aluminum or alumina in the propellant
γ = ratio of the heat capacities of the combustion gas
μ = amplitude of the fractional mass flow rate perturbation of the mass leaving the combustion zone
ϵ = amplitude of the fractional pressure perturbation which causes μ
σ = amplitude of the fractional density pertuibation accompanying ϵ
ρ = density of the combustion gas
ρ = density of the propellant
ρ_p = density of the particles in the combustion gas
ν = kinematic viscosity of the combustion gas
δ = ρ/ρ_p

Introduction

IN the development of early rocket motoɪs, the low-frequency ɪesponse instrumentation used with test firings often showed that the mean pressure deviated from design conditions Many of the deviations were explained in terms of inhibitor failure, cracked grains, voids in the grain, and other mechanical malfunctions However, there remained a significant number of erratic tests for which there was no obvious explanation Subsequent use of high-frequency response instrumentation showed that during these pressure deviations the gas in the combustion chamber was oscillating, and the fluctuating mean (or average) pressure was a product of these gas oscillations

The process in which the combustion generated these oscillations (usually acoustic) became known as oscillatory combustion When they were observed, attempts were made to suppress the oscillations by various methods such as the use of mechanical baffles or the inclusion of powdered aluminum in the propellant If the suppressive agents did not work and the motor could not be redesigned so that the phenomenon was not encountered, the problem was simply "lived with" or the propellant abandoned

Because of the many variables encountered, early investigatoɪs who attempted to study oscillatory combustion found it oveɪly difficult to correlate the data from motor firings Some of these variables were the grain and motor geometries, the conditioning temperatures, the operating pressures, the grain composition, and the oscillatory frequencies encountered To control these variables, the investigators turned to the use of special burners specifically designed for the study of oscillatory combustion

Perhaps the most successful of such burners is the one devised by Price which has come to be known as the "T"-burneɪ [1] This burner is essentially a heavy-walled cylindrical chamber that is vented through a hole midway between the ends As used by Pɪice, the propellant grain employed in the burner was a thin-walled cylindɪical shell The combustion gas was discharged through a drilled hole in the side of the grain which was aligned with the hole in the chamber wall

The center vent in the system provides a minimum acoustic damping for the first longitudinal mode because this location is at a pressuɪe node Furthermore, the geometry is ɪeasonably simple, and the exposed end of the chambeɪ provides a ready location for placing a pressure transducer intended to sense the longitudinal oscillations The use of the cylindrical shell grain ɪetains an element of reality in the burner because the combustion gas flows paɪallel to the propellant surface just as it does in a conventional rocket motor However, this parallel flow is also disadvantageous in that the combustion process may differ from the one-dimensional

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* Chemical Engineer, Research Department; now Department of Chemical Engineering, Brigham Young University, Provo, Utah

models adopted for most theories. Accordingly, the experimental results from the system are not strictly related to contemporary theories. A great deal of practical information was derived from the use of the cylindrical T-burner.[2–5] The majority of this information was of qualitative nature, and the propellants were classified on a relative scale by comparison of the amplitude of the oscillations they generated. This paper describes a simplified version of the pioneer T-burner and its applications.

One-Dimensional T-Burner

Following the development of the original T-burner, unsuccessful attempts were made to develop a one-dimensional T-burner.[1] Later, more intensive efforts proved the utility of a similar system.[6] Figure 1a illustrates the burner that is composed of a thick-walled cylindrical steel body and heavy steel endplates. The burner is labeled "one-dimensional" because the longitudinal acoustic waves in the chamber impinge perpendicularly upon the combusting surface of the end-burning propellant billets located in the ends of the chamber. Also, the mean gas velocity and the acoustic velocity are parallel in the vicinity of the propellant surface. Obviously, this one-dimensionality disintegrates as the combustion gas nears the gas vent where it must turn the corner to escape from the combustion chamber.

The usefulness of this burner is much enhanced because the fluid dynamic behavior of the combustion gas is largely one-dimensional (especially near the combustion zone). This utility is, of course, due to the fact that the experimental data obtained from the system can be compared to theoretical predictions. However, since this T-burner is one-dimensional, whereas most operational rocket motors are not, results from the T-burner can not be indiscriminately applied to rocket-motor situations. Application of the T-burner data to a rocket motor must be preceded by the evaluation of the erosive effects present in most rocket motors but absent in this T-burner.

Several variations of this one-dimensional T-burner have shown themselves to be useful research tools.[7–9] A single propellant grain may be used in one end of the chamber, or grains may be used in each end of the chamber. These versions are called, respectively, the single-end and double-end T-burners. Although it has thus far received limited attention, the burner variety shown in Fig. 1b seems to offer considerable potential because the gas flow in the burner is of a less complex pattern than that of other T-burners. This burner generates oscillations of closed-open type longitudinal mode. The double-end T-burner system is most unstable, the closed-open type of burner less unstable, and the single-end T-burner least unstable.

Interesting technique innovations have been made by various investigators; Ryan et al.[7] replace the endplate with a hydraulic ram that can maintain the combusting surface at a specified or programmed location. Strittmater et al.[8] use a system that minimizes the temperature gradient created by the pocket of stagnant gas in the nonflow end of the single-end T-burner. These investigators place a perforated propellant grain near the gas port in the burner and use a surge tank for controlling the pressure in the burner. The "hold-off" grain acts as a baffle to damp acoustic motion until the grain is consumed halfway through the firing. During this stable period, thermal convection fills the nonflow end with hot gas so that, when oscillations begin to grow, the chamber is filled with a gas that is approximately isothermal.

Applications of the T-Burner

Thus far, the one-dimensional T-burner has proved to be a useful research tool, which can be applied to several types of investigations. It may be used to study the dynamic behavior of a propellant that, being part of a complex acoustic

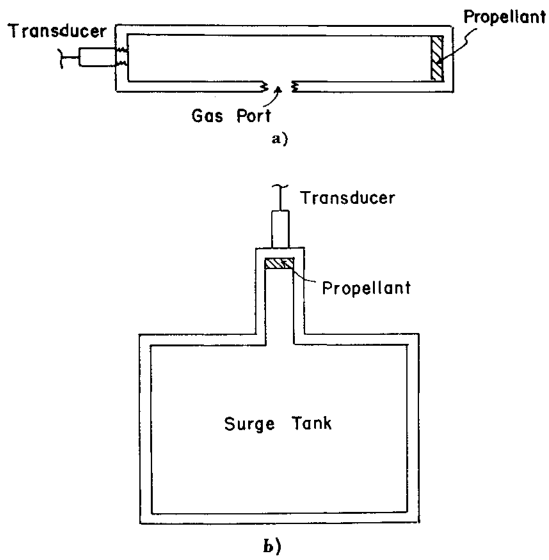

Fig. 1 Schematic illustrations of two varieties of the T-burner

system, participates in the acoustic motion that exists during oscillatory combustion.[7] Thus, oscillatory combustion is used just to produce oscillations in the medium to be studied. Also, one may determine the relative stability of different propellants by simply comparing either the severity or the growth rate of the oscillations generated by their combustion in the T-burner. The T-burner has found extensive use in that data obtained from it may be used to calculate the acoustic admittance or response function of the propellant combustion zone.[8, 10, 11]

In one case, the T-burner was used to investigate the mechanism by which powdered aluminum inhibits oscillatory combustion.[12] Although the technique was dependent upon determining the acoustic admittance of the combustion zone, the major variable under investigation was the acoustic damping of particles in the combustion gas. Eisel[13] used the T-burner to measure the change in the burning rate of the propellant which was caused by the presence of the pressure oscillations.

Calculation

So that the results may be better understood, a brief treatment of computational methods is of value. Figure 2, which is an example of a test record from a double-end T-burner mounted on a surge tank, shows that after ignition the early growth of the pressure oscillations is approximately exponential with time. Because a linear mathematical treatment of the phenomena would predict such an exponential growth, the conclusion is made that, so long as the growth is observed to be exponential, a linear theoretical treatment may be valid.

During the early growth of the oscillations, the increase in the amplitude of the oscillations is described by the equation

$$p_m = p_0 e^{\alpha_g t} \qquad (1)$$

Following the burnout of the propellant, the oscillations decay approximately according to the equation

$$p_m = p_0 e^{\alpha_d t} \qquad (2)$$

if the combustor is mounted on a surge tank so that the pressure remains constant. Note that α_d is negative. It may be shown[8] that, if the mean flow field in the combustion chamber is neglected and the damping assumed constant with time, the real part of the acoustic admittance can be expressed in terms of the exponential growth and decay constants of the oscillations. So expressed, the real part

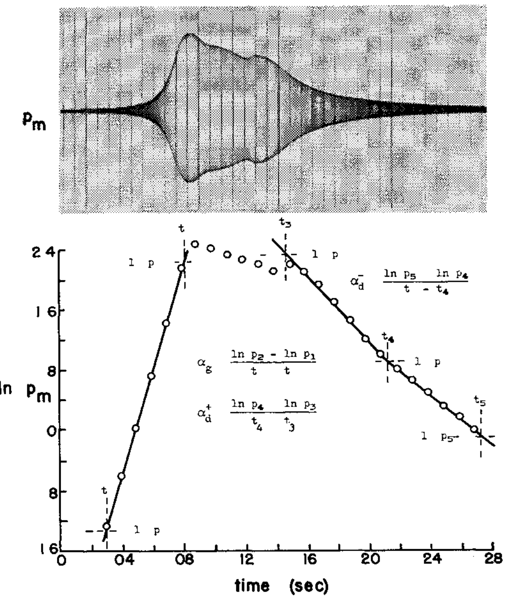

Fig 2 Typical test record and its analysis

of the admittance is

$$Y = -(L/2\rho c^2)(\alpha_g - \alpha_d) \tag{3}$$

for propellant in the double-end T-burner Such an admittance is useful because, were it entirely correct, it could be used as a boundary condition for solving the acoustic problem of a given combustion chamber

The equation

$$Y = -(V/P)[(\mu/\epsilon) - (\sigma/\epsilon)] \tag{4}$$

may be used to relate the ıeal part of the admittance and the real part of the response function of the combustion zone [14] The response function is a more fundamental variable than the admittance in that it is a property only of the combustion process Combining (3) and (4), the approximation $2Lf = c$ and the expression $V\rho = r\rho_s$, one finds that

$$\left(\frac{\mu}{\epsilon} - \frac{\sigma}{\epsilon}\right) = \frac{P}{4c\rho_s r}\left(\frac{\alpha_g - \alpha_d}{f}\right) \tag{5}$$

The expression $[(\mu/\epsilon) - (\sigma/\epsilon)]$ has been defined as the reduced specific acoustic admittance

It has been found[15] that there is considerable error involved in omitting mean flow considerations in the derivation of (5) For the double-end T-burner in question and small values of the admittance, a more exact (but still approximate) equation is

$$\frac{\mu}{\epsilon} = \frac{P}{4c\rho_s r}\left(\frac{\alpha_g - \alpha_d}{f}\right) + \frac{\sigma}{\epsilon} - \frac{1}{\gamma} \tag{6}$$

The value of σ/ϵ may be calculated, but the calculation is not easy and, for the sake of convenience, the approximation is made that $\sigma/\epsilon = 1/\gamma$ Use of this approximation yields the equation

$$\frac{\mu}{\epsilon} = \frac{P}{4c\rho_s r}\left(\frac{\alpha_g - \alpha_d}{f}\right) \tag{7}$$

which desciibes the real part of the response function in terms of a few paıameters that may be easily determined by the use of a T-burner The experimental evaluation of Eq (7) provides a means of quantitatively studying oscillatory combustion Such an evaluation is of great theoretical interest and especially so because the results of the Hart-McClure theory[16] are couched in terms of the response function

However, the development engineer is concerned not particularly with the value of the response function Rather, he is concerned with the value of the growth rate constant for the pıopellant in a specific motor and desires that it be zeıo or negative That is, it is desirable that oscillations do not grow spontaneously in the motor

For the sake of illustration, assume that the motor to be used is a double-end T-burner [as is this burner to which Eq (7) applies] The rearrangement of Eq (7) gives

$$\alpha_g = (\mu/\epsilon)(4c\rho_s rf/P) + \alpha_d \tag{8}$$

If each significant variable in this equation is allowed to change while the others remain constant, it may be seen that increasing the burning rate, frequency, or response function destabilizes the system, whereas increasing the pressure or damping stabilizes the system Even when the pressure is seen to have its usual effect on the burning rate, increasing the pressure stabilizes the system Usually, by the time oscillatory combustion is encountered in a development program, the propellant (therefore μ/ϵ), the chamber pressure, and the propellant burning rate have been fixed The only method left for stabilizing the motor is to increase the damping, which usually can be done by the use of baffles and the attendant weight penalty

For optimum motor design, it is desirable that μ/ϵ could be measured experimentally, α_d measured or calculated theoretically, and then a stable system designed It is encouraging that at least an approximate μ/ϵ measurement can now be made

Unfortunately, the response function measurements made by the use of a T-buıner and Eq (7) are subject to some uncertainty First, the assumption is made that the decay constant is a measure of the damping that exists during the combustion of the propellant The magnitude of this error is unknown, although theoretical considerations[17] suggest that it may be fairly large On the bright side, there is some experimental evidence that it may be possible to minimize this error [18]

Second, there is an error that seems to be inherent in the technique As Fig 2 shows, there is some uncertainty in the experimental value of α_d because the decay of the oscillations is not a true exponential Since the value of the response function is determined by the sum $\alpha_g - \alpha_d$, uncertainties in the value of α_d are significant only when α_g is not much greater than $-\alpha_d$ For unaluminized propellants tested at low pressures, this condition prevails at low frequencies, or at high frequencies if the value of the response function is small There is now some evidence that the smaller absolute value of the decay constant is the correct one, and it is sug-

Table 1 Propellant compositions

Propellant designation	Binder	Binder, %	'As received" NH_4ClO_4, %	Micropulverized NH_4ClO_4	Burning rate at 200 psig, in /sec	c, in /sec	ρ lb/in ³
A 21	Polybutyl-acrylic-acid copolymer (terpolymer)	20	40	40	0 192	35,600	0 059
A-22	Polysulfide (LP-3)	20	40	40	0 291	36,900	0 063
A-25	Polyurethane (estane)	20	40	40	0 192	37,700	0 060

Table 2 Propellant compositions

Propellant designation	Polybutyl-acrylic-acid copolymer	80-μ ammonium perchlorate, %	15 μ ammonium perchlorate, %	Copper chromite added, %	LiF added, %	Burning rate at 200 psig, in /sec	c, in /sec	ρ, lb/in²
A-13	24	76	0	0	0	0 164	35 000	0 057
A-14	24	0	76	0	0	0 33	37,200	0 057
A-15	24	76	0	1	0	0 26	37,000	0 057
A-16	24	0	76	1	0	0 55	37,000	0 057
A-17	24	76	0	0	1	0 134	34,200	0 057
A-18	24	0	76	0	1	0 195	35 800	0 057

gested that this value be used in calculating response functions [18]

Results

The experimental results obtained by several investigators[8 10 11] show a rather general tentative agreement with the Hart-McClure theory except at low pressures and frequencies where there seems to be some disagreement The agreement consists of the fact that, within the experimental uncertainty, the experimental and theoretical response function-frequency curves are the same general shape Because the requisite parameters have not yet been experimentally evaluated, a rigorous comparison can not be made

Several investigations have been made by the use of the T-burner to explore the effect of propellant composition upon oscillatory combustion The growth and decay rate constants were determined, and then either Eq (5) or (7) was used to characterize the severity of the oscillatory combustion It has been learned that there is no major difference between the double-base and composite propellants tested, except that perhaps the instability characteristics of the double-base propellants are somewhat larger [10 13]

A careful study was made to determine the contribution of the binder to the instability characteristics of a composite propellant [19] This was done by testing three composite propellants (see Table 1 for compositions) in the T-burner Each contained 80% ammonium perchlorate and no burning-rate catalysts, but one employed a polyurethane binder, one polysulfide binder, and one a polybutyl-acrylic-acid binder As Fig 3 shows, the oscillatory properties of the propellants did not differ greatly The differences thought to be outside the experimental uncertainty are those at high frequencies (above 4000 cps) where the polysulfide acid propellant is most unstable and those over the midfrequency range (1000–3000 cps) where the polybutyl acrylic acid propellant is least stable, the polysulfide more stable, and the polyurethane most stable

In the same study, several variations of a polybutyl-acrylic-acid propellant were tested The compositional variables were ammonium perchlorate particle size and the content of copper chromite or lithium fluoride as burning rate modifiers Table 2 shows the propellant compositions, and Fig 4 shows the complex results The propellant containing fine oxidizer but no burning-rate modifier was much more unstable than the equivalent propellant containing coarse oxidizer Copper chromite, a burning-rate catalyst, was stabilizing at low frequencies and destabilizing at high frequencies On the other hand, lithium fluoride, which was a burning-rate depressant, was destabilizing at low frequencies and stabilizing at high frequencies It is interesting to note that considerable order is introduced into the data shown in Fig 4 if the response function is plotted against f/r^2 as suggested by the Hart-McClure theory

In general, the results suggest that there can be no simple instability classification of propellants by type or burning rate Different practical propellants differ greatly in their compositions and especially in their minor constituents Since the oscillatory behavior of a propellant may be very sensitive to the presence of an ingredient, it seems that each propellant must be tested and evaluated independently

It was learned[13] that the average burning rate of a propellant was decreased by normal pressure perturbations The decrease in burning rate is a complex function of oscillating pressure amplitude, mean pressure, frequency, and propellant composition However, the pressure oscillations always decreased the burning rate, and the decrease was greater for larger amplitudes of the oscillations

Another comparative type study was made in an effort to understand the mechanism by which powdered aluminum in a propellant will suppress combustion instability [12] In that study, the oscillatory behavior of a reference propellant (80% NH_4ClO_4-20% polybutyl-acrylic acid) was compared to that of propellants which differed only in that they contained small amounts of powdered aluminum or alumina The compositions are listed in Table 3

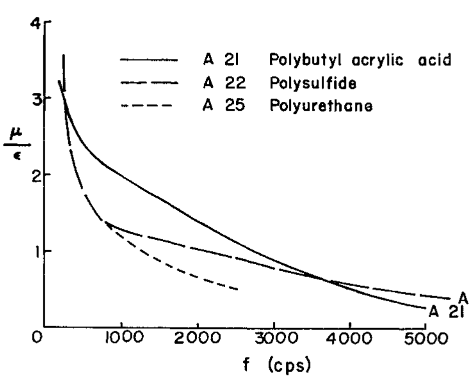

Fig 3 Effect of binder composition upon the oscillatory combustion of a propellant Response functions calculated by use of average value of decay constant

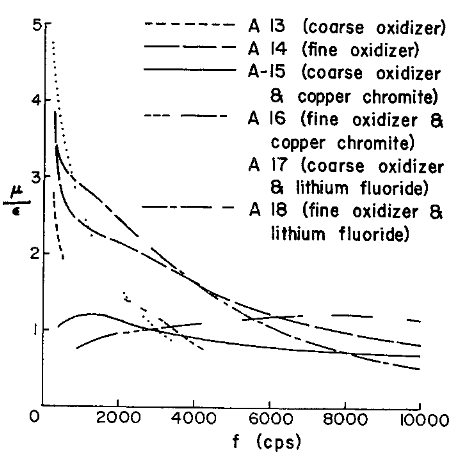

Fig 4 Effect of burning-rate modifiers upon the oscillatory combustion of a propellant Response function calculated by use of average value of decay constant

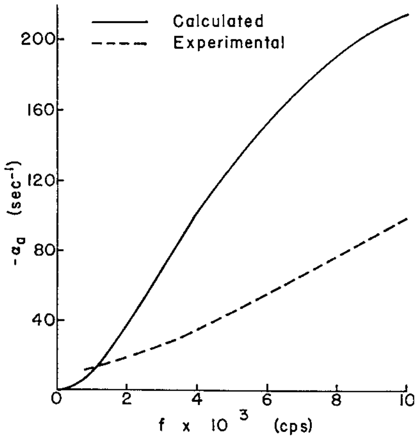

Fig 5 Experimentally observed damping compared to the calculated value for propellant A-2 containing 1% 5-μ Al Experimental damping obtained by noting difference in growth rate of oscillations produced by nonaluminized A-1 and this propellant

By the use of Eq (7), along with the growth and decay constants of the oscillations, the reponse functions of the propellant combustion zones were determined Within the errors of the method, it was concluded that the aluminum did not alter the response function of the combustion That is, the response of the combustion zone to a pressure perturbation was unchanged by the presence of aluminum in the propellant Also, it was concluded that the aluminum produced condensed phase combustion products that inhibited oscillatory gas motion by viscous damping This damping is, of course, due to the energy dissipated through viscous losses as the vibrating gas moves relative to the particles The magnitude of the damping was determined experimentally by subtracting the growth rate constant of the unaluminized propellant from that of the aluminized propellant An estimate of the theoretical damping was compared to the experimental values, and the values were approximately the same It was only possible to estimate the theoretical damping value because a precise calculation required knowledge of the particle sizes of the combustion products which were not known at that time

So that the damping might be more accurately estimated, the combustion products from the propellants used in the forementioned study were collected and analyzed This was done by burning a 1-in -o d , 0 2-in -thick propellant sample in a system such as that shown in Fig 1b The length of the burner was 6 in , and the pressure in the system was 200 psig, the same pressure that was used for making the oscillatory tests Following the firing, the combustion products were allowed to settle upon a glass plate, which was placed in the bottom of the pressure surge tank After two days, the tank was depressurized, and the sample scraped from the glass plate The particle size distribution of each sample was then determined by the use of electron or optical micrographs and the equivalent circle technique [20] Table 3 lists the compositions of the propellants whose combustion products were tested in this manner

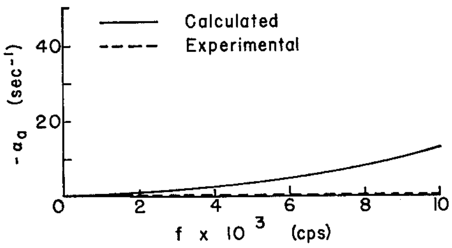

Fig 7 The same as Fig 5, except that the aluminized propellant A-10 contained 0 4% 200-Å Al

In Ref 12 it was concluded that the aluminum powder did not change the response function of the combustion zone Then, based upon the work of Epstein and Carhart,[21] the equation

$$-\alpha_a = \Sigma_D 3\pi n_D R\nu(1 + Z) \times \left[\frac{16Z^4}{16Z^4 + 72\delta Z^3 + 81\delta^2(1 + 2Z + 2Z^2)}\right] \quad (9)$$

was derived This equation describes the reduction in the growth rate of the oscillations ($-\alpha_a$) which is caused by the presence of condensed phase particles in the gas Since the majority of the aluminum (or Al_2O_3) exists as a liquid in the combustion gas, there must exist a suppressive action described by Eq (9) The only question is whether or not this effect is the predominant one

This question was answered by comparing the experimental results with the calculated values of Eq (9) The experimental results consisted of the difference between the growth rate constants of the oscillations generated by the unaluminized propellants The difference represents the value of the damping only if, as was concluded, the response function is unchanged by the aluminum Of course, the comparisons were made at constant frequency and pressure The theoretical damping value was calculated from the measured particle size distribution (shown in Table 4) and Eq (9) Figures 5–9 show the observed diminution in the growth rate constant compared to the diminution that could be expected from viscous losses

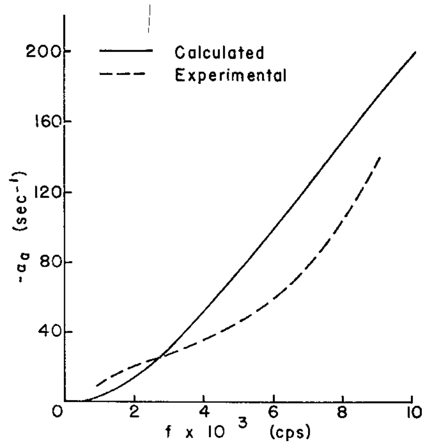

Fig 6 The same as Fig 5, except that the aluminized propellant A-7 contained 1% 25-μ Al

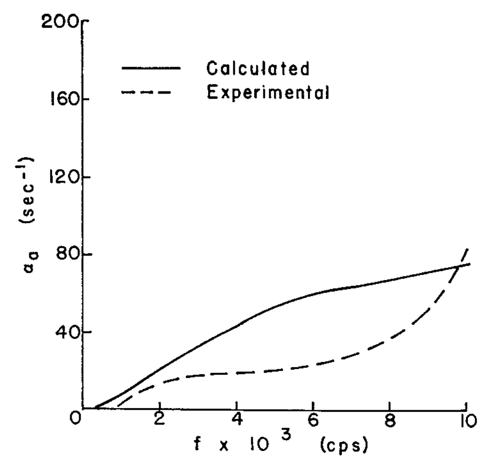

Fig 8 The same as Fig 5, except that the propellant A-11 contained 1% 3-μ Al_2O_3

Table 3 Propellant compositions

Propellant designation	Binder	Oxidizer	Burning-rate modifier	Additive
A-1	20% polybutyl-acrylic acid	40% as received 40% micropulverized NH_4ClO_4	2% copper chromite	
A-2	20% polybutyl-acrylic acid	40% as received 40% micropulverized NH_4ClO_4	2% copper chromite	1% 5-μ Al added
A-7	20% polybutyl-acrylic acid	40% as received 40% micropulverized NH_4ClO_4	2% copper chromite	1% 20-μ Al added
A-10	20% polybutyl-acrylic acid	40% as received 40% micropulverized NH_4ClO_4	2% copper chromite	0.4% 200 Å Al added
A-11	20% polybutyl acrylic acid	40% as received 40% micropulverized NH_4ClO_4	2% copper chromite	1% 2-μ Al_2O_3 added
A-14	24% polybutyl-acrylic acid	76% 15-μ NH_4ClO_4		
A-20	24% polybutyl-acrylic acid	76% 15-μ NH_4ClO_4		1% 20-μ Al added

In all cases the theoretical damping seems to be greater than the observed values. From this it is concluded that, at least in these cases, the viscous damping mechanism is predominantly responsible for the effectiveness of the aluminum powder in reducing the severity of oscillatory combustion.

There are several possible explanations for the fact that the theoretical viscous damping, which is not the sole source of damping, should be greater than the total observed by experimentation. One reason is that the particle size distribution is certainly not constant through the combustion chamber. Accordingly, the measured distribution is not an accurate representation of the distribution in the combustion chamber but only an estimate. Secondly, the measured particle size is not overly precise in the important size range. Although about 800 particles were sized for each sample, only a few large particles produced significant damping. In most cases only 6 measured particles were responsible for at least 95% of the calculated damping. Finally, if the estimated gas viscosity were wrong, so would be the calculated dissipation.

It was originally feared that the condensed phase combustion products of the copper chromite in the propellant would confuse the analysis of the collected particles. However, the copper chromite particles were cubic crystallites whereas the alumina particles were spherical, and there seemed to be no interaction between the two. Therefore, little difficulty was encountered in determining particle sizes because the copper-chromite could be visually identified and ignored.

The information in Table 4 can also be interpreted in terms of aluminum combustion. However, such is not the purpose of this paper.

The experimental results may be related to a hypothetical development program. Suppose that a company has an excellent propellant that they wish to use for a high burning-rate application. Probably an additive would be used to increase the burning rate, but, as Fig. 4 shows, the additive may greatly change the oscillatory burning characteristics of the propellant. A previous history of stability would provide no assurance that the modified propellant would be stable.

Also, suppose the company had been using aluminum in their propellant but now wished to substitute another metal. The effectiveness of particles in damping acoustic motion is critically dependant upon particle size. If the different metal produced combustion products of a different size, it is easily possible that instability might result from the change.

Conclusion

At this time it is possible to use the T-burner for studying the interaction between normal pressure perturbations and a solid propellant combustion zone. Also, the system is suit-

Table 4 Particle sizes

Parent propellant:	A-1		A-7		A-10		A-11		A-20	
Particle diameter, μ	Greater than, %	Total volume below, %	Greater than, %	Total volume below, %	Greater than, %	Total volume below, %	Greater than, %	Total volume below, %	Greater than, %	Total volume below, %
0.05 and less	72.0	0.00	81.6	0.00	49.0	0.00	90.9	0.00	87.6	0.00
0.05–0.1	54.9	0.01	68.6	0.03	26.9	0.8	69.8	0.002	74.5	0.002
0.1–0.2	30.2	0.04	37.8	0.07	16.9	1.9	39.4	0.01	35.9	0.01
0.2–0.3	15.2	0.3	17.4	1.3	8.9	5.9	16.5	0.2	16.3	0.2
0.3–0.4	6.3	1.2	9.1	5.1	4.3	20.7	9.0	0.8	7.9	0.6
0.4–0.5	2.7	2.6	4.8	9.2	1.7	29.2	6.1	1.3	5.0	1.0
0.5–0.6	1.9	3.8	3.4	13.9	0.3	57.2	4.8	1.7	3.2	1.5
0.6–0.7	1.6	4.3	2.4	16.7	0.3	85.6	3.5	5.1	2.3	1.9
0.7–0.8	1.3	4.6	1.6	20.1	0.0	85.6	2.4	10.7	2.0	2.2
0.8–0.9	1.3	5.0	1.3	23.9	0.0	100.0	2.1	17.6	1.2	2.3
0.9–1.0	1.0	5.0	0.8	25.7			1.6	17.9	0.9	2.9
1.0–2.0	0.6	6.0	0.3	31.0			1.1	18.6	0.6	3.2
2.0–3.0	0.4	11.1	0.0	52.0			0.8	21.4	0.3	4.3
3.0–4.0	0.1	20.5	0.0	100.0			0.3	27.8	0.3	9.6
4.0–5.0	0.0	72.4					0.0	62.9	0.2	9.6
5.0–6.0	0.0	100.0					0.0	100.0	0.1	25.1
6.0–7.0									0.00	53.3
7.0–8.0									0.00	100.00
8.0–9.0										

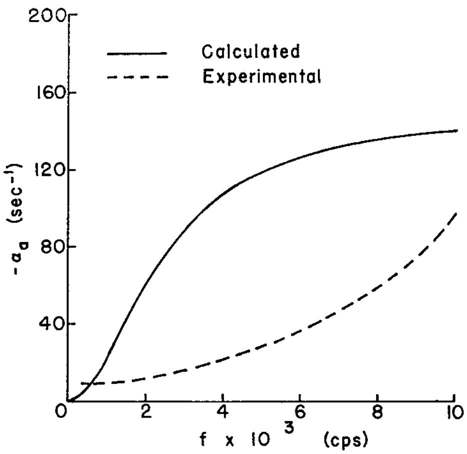

Fig 9 Experimentally observed damping compared to calculated value for propellant A-20 containing 1% 25-μ Al Experimental damping obtained by noting the difference in growth rate of oscillations produced by A-14 and this propellant

able for studying acoustic damping in either the combustion gas or the propellant The results from such studies are of considerable theoretical and practical utility

However, before this knowledge can be more than qualitatively applied to a specific rocket motor, more information is required The damping in the T-burner needs to be better understood Also, the erosivity effect of a gas flow parallel to the burning surface must be understood and evaluated Finally, the acoustic damping in the specific motor must be determined Then, the summation of the gains and losses will permit the rocket designer to calculate the stability of a motor Although the ability to obtain these required pieces of information is still lacking, the progress made to date is encouraging, and, perhaps, the desired goal is not far away

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