Experimental Study of Pressure Wave Propagation in Granular Propellant Bed

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The ignition transients and penetrative burning characteristics of confined granular propellant beds in a cylindrical tube (loading densities up to 1.03 g cm^3 and pressures up to 4000 bar) were investigated to test the 1-D pressure-wave propagation profiles predicted by the 1971 Kuo-Vichnevetsky-Summerfield analytical model. Thus, it was found that following the initial pressure rise along the bed, the position of peak pressure occurs within the bed and progresses downstream at an accelerating rate. The ignition time of the granular bed increases sharply with decreasing loading density. Wall friction acting on the unburned propellant along the tube attenuates downstream transmission of solid phase pressure generated by the upstream burning processes. This work has applications to the internal ballistics of guns, deflagration to detonation transition, and fast-burning rocket charges.

Introduction

EXPERIMENTAL studies of ignition, flame spreading, and pressure wave propagation through beds of granular solid propellant were prompted by the desire to understand the operation of propelling charges and to isolate conditions under which controlled ultra-high burning rates can be achieved. Pressure gradients in the chamber drive the hot combustion gases into the passages (i.e., the spaces between the granules) of the unburned propellant, which in turn convectively heats the propellant to ignition. This process usually results in an accelerating flame front when the combustion chamber is highly loaded. As described in Ref. 1 for steady-state burning, the mechanism of convective flame propagation through granular propellant beds can vary from relatively slow to ultra-high velocities. The higher the pressure differential between the combustion wave and the unburned propellant, the greater the rate of penetration of the combustion gases into the unburned section of the propellant bed and, consequently, the greater the combustion wave velocity.

The study concentrates on ignition and burning at pressure levels corresponding to the regions studied theoretically by Kuo, Vichnevetsky, and Summerfield.[1,2] Typically, we are concerned with pressures up to 60,000 psi (4000 bar) and wave propagation velocities on the order of 100 mps.

The analytical model of Kuo, Vichnevetsky, and Summerfield[1] (KVS model) calculated the pressure-time-distance transient [i.e., wave propagation speed as well as $p(x,t)$] and mass fractions of burning granular propellant beds. The KVS calculated results agreed with the experimental data of Squire.[3] Kitchens[4] developed an alternative numerical solution to the KVS formulation and carried out parametric studies. Additional analytical treatments are now in progress by Gough,[5] Krier,[6] and Frolov.[7]

Recently, Gerri and co-workers[8,9] obtained data on the combustion of long propellant beds (10.84[8] and 20.16[9] cm long; 7.76 mm i.d.). They found that the initial primer/propellant interaction is of great importance and that either poor or excessively strong ignition lead to excessive pressures and erratic pressure profiles. In their earlier study,[8] it was concluded that the burst diaphragm is ruptured by force transmitted through the propellant bed. However in their latter study,[9] they reverse their position after finding that the peak pressure generated in the combustor was independent of the shear strength of the burst diaphragm. They concluded[9] that bed compaction and radial frictional forces must play an important role in long beds.

The purpose of this study was twofold: 1) to confirm the one-dimensional pressure wave propagation first predicted by the KVS analytical model, and 2) to examine the influence of experimental parameters such as propellant loading density, combustor orientation, primer variability, and blow-out diaphragm thickness on the propellant bed wave characteristics. Originally, the verification of the KVS model was based on a limited amount of experimental data[3] (which was available in 1972) and therefore a comparison of the analytical predictions with a wider range of experimental data was sought. With increasing interest in developing analytical methods for predicting the transients of flame front and pressure wave propagation, we placed emphasis on obtaining systematic data (influence factors of experimental parameters) which can be used to test the validity of the future theoretical models.

Experimental Apparatus

The experiments were carried out by igniting and burning beds of granular propellants in a cylindrical chamber shown schematically in Fig. 1. This is a version of the combustor described by Squire in Ref. 3. The reader is cautioned that several combustors similar to the Fig. 1 combustor have been used by Squire and by Gerri and that unless the dimensions are identical to those of Fig. 1, the data are not directly comparable. Three ports at prescribed locations along the combustor axis provide the access for measuring pressures along the granular bed. The location of the three pressure gauges G1, G2, and G3 relative to the igniter are shown in Fig. 1. The ultra-high frequency Kistler 607A pressure transducers were used to monitor the pressure transients. At the upstream end of the chamber, a percussion actuated primer was used to provide the flow of hot gases to ignite the granular propellant bed. At the downstream end of the chamber, a diaphragm was used to confine the gaseous combustion products until the pressure experienced by the diaphragm was sufficient to rupture it. The circular shaped diaphragms, of 304 stainless steel, were 0.076 cm thick. However, special experiments were performed utilizing diaphragm thicknesses ranging from 0.013 to 0.076 cm.

A volumetric loading of 100% was established by weighing the amount of propellant required to completely fill the chamber; the bed was vibrated but not packed. This was repeated 20 times and the weights were averaged to establish the stan-

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Index categories: Combustion in Heterogeneous Media; Combustion Stability, Ignition, and Detonation.

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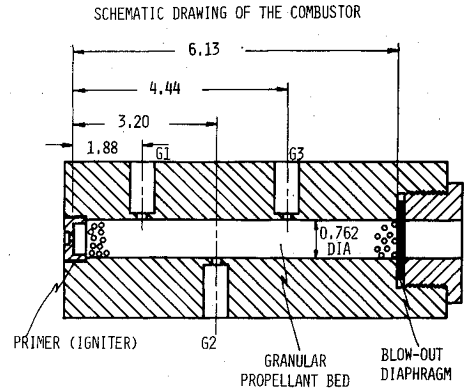

Fig.1 Schematic drawing of the combustor showing position of three pressure ports and diaphragm relative to primer (dimensions in centimeters).

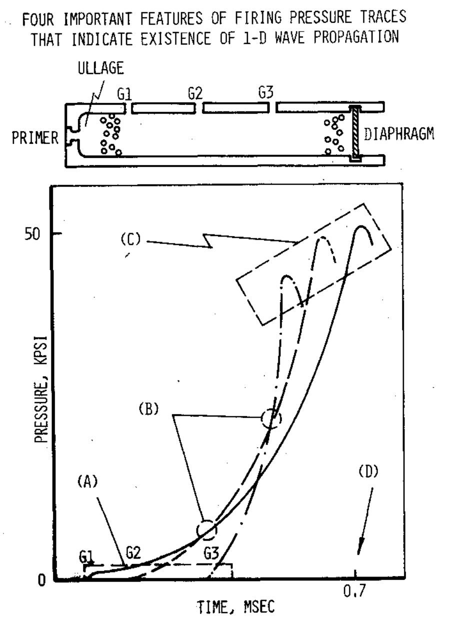

Fig.2 Four important features of firing pressure traces that indicate existence of 1-D wave propagation: (A) Gauges start to rise in ordered sequence. (B) G2 overtakes G1, and then G3 overtakes G2. Shows existence of peak pressure within the propellant bed. (C) Expansion wave after diaphragm burst passes G3 first, then G2 and G1 in sequence. (D) G1 senses diaphragm burst.

Table 1 WC 846 propellant composition and combustion gas properties

Overall composition, % mass

80.0 nitrocellulose (13.15%N)
10.0 nitroglycerin
5.0 dibutylphalate
1.0 diphenylamine
0.4 graphite
3.6 moisture and other volatiles

Typical particle size distribution[a]

U.S. Sieve No.	Micron	%Retained
20	840	0.01
25	710	1.71
30	590	23.86
35	500	51.41
40	420	21.44
45	350	1.19
50	297	0.01
PAN		0.01

Properties

Isochoric flame temperature = 2834 K
Average molecular weight = 23.4 g/g mole
Force = 336,200 ft lbf/lbm
Ratio of specific heats = 1.25

[a]the granules are oblate spheroids deterred by dibutylphalate to about 20% of the mean radius.

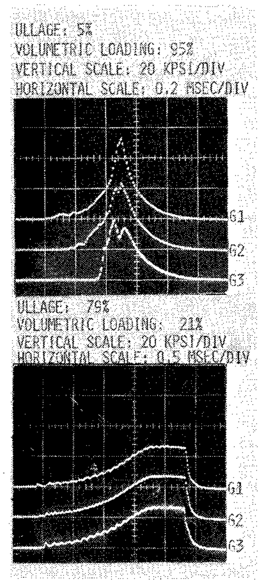

Fig. 3 Elimination of 1-D propagating wave characteristics when volumetric loading is small. (Propellant: WC846, Primer: FED 200, combustor axis orientation: vertical, primer at bottom.

dard weight for 100% loading. Thus, for example, a volumetric loading of 90% is 90% standard weight and the corresponding ullage is 10% of the empty chamber. Ullage was taken to be the volume of the chamber not occupied by the granular bed. Accordingly, 2.924 g of WC846 ball propellant were required for 100% volumetric loading or a bed density of 1.03 g/cm^3. The density of an individual granule of WC846 is 1.60 g/cm^3. The loading density is based on a measured volume which includes the small volume in the pressure ports.

The chemical composition and combution gas properties of the WC846 ball propellant used throughout the experiments are given in Table 1.

Results and Discussion

Figure 2 is a schematic representation of typical pressure traces obtained in the present experiments for the loading density range of about 0.80-1.10 g/cm^3. The important features of the experimental pressure traces which indicate the existence of one-dimensional wave propagation as predicted by the KVS analysis are designated by the letters and described in the caption of Fig. 2. Of particular importance is event *B*,

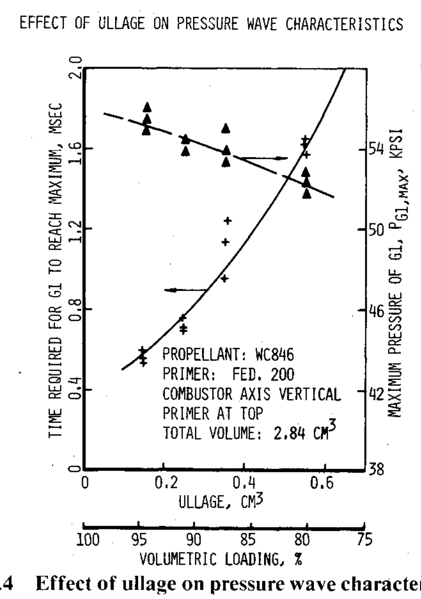

Fig.4 Effect of ullage on pressure wave characteristics.

which shows the existence of peak pressure within the granular bed (i.e., the so-called continental divide). Following the advancement of the ignition front, the peak pressure within the granular bed moves toward the diaphragm-end of the combustor and produces the two cross-overs observed on the pressure traces.

At low loading densities (e.g. <0.5 g/cm^3) the one-dimensional propagating wave characteristics of porous propellant beds are eliminated. This elimination is attributed to the high porosity of the mobile propellant bed, that diminishes the combustion-generated pressure gradients that constitute the driving force of the ignition wave propagation. Figure 3 shows a comparison of the pressure traces obtained at high and low loading densities of the combustor. The pressure traces in the lower part of Fig. 3 (low loading density) show none of the one-dimensional accelerating wave characteristics observed in the pressure record. Of interest are the pressure oscillations experienced by the three gauges at low loading density. These are longitudinal waves which are within 5% of the theoretical frequency. The double frequency sensed by the center transducer is indicative of the nonlinearities of the longitudinal wave.

The effect of ullage on the pressure wave characteristics of granular propellant charges is shown in Fig. 4. As the free volume increases, the time required for the pressure at G1 to reach maximum, t_{G1}, increases. With increase in ullage, the pressure of the gases produced by the primer and the pressure gradients within the granular bed are lower, and therefore ignition and the subsequent convective mode of burning of the granular propellant bed are slower (also see Fig. 5). This increase in t_{G1} illustrates the dominance of the steep pressure gradient in accelerating the flame spreading process. Increasing ullage decreases the maximum pressure attained by G1.

As defined in Fig. 5, the time for G1 to achieve maximum pressure t_{G1} can be divided into two periods: the time delay to rapid increase in pressure (t_{rs}) as defined by the tangent intersection shown in Fig. 5, and the time period from onset of rapid pressure rise to peak pressure (t_{rp}). With all other test conditions held constant, the pressurization period, t_{rp}, is nearly independent of ullage and the delay (t_{rs}) increases rapidly with increasing ullage.

For high volumetric loadings (small ullage) the increase in the period t_{rs} is approximately linear with increasing ullage. At the same time t_{rs} is approximately inversely proportional to the rate of production of igniter combustion gases. Therefore, for a given propellant type (in this case WC846)

$$t_{rs} = K \frac{V_u}{(m_{pr}/t_{pr})}$$

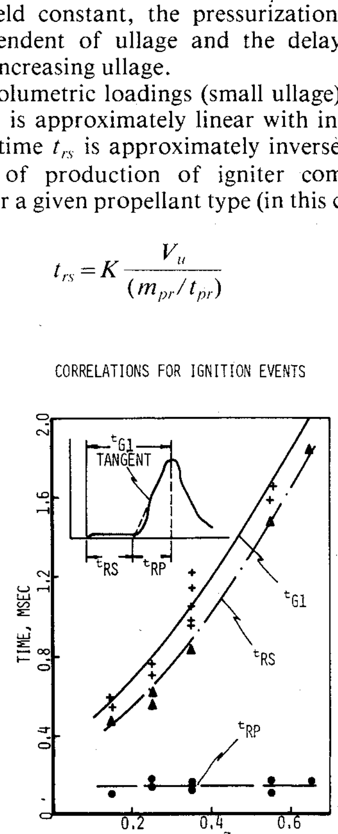

Fig.5 Correlations for ignition time of granular propellant bed.

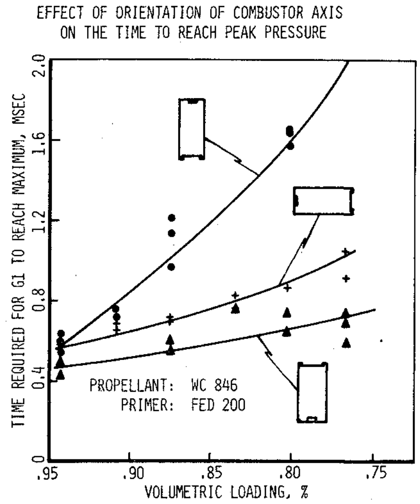

Fig.6 Effect of orientation of combustor axis on the time for G1 to reach peak pressure.

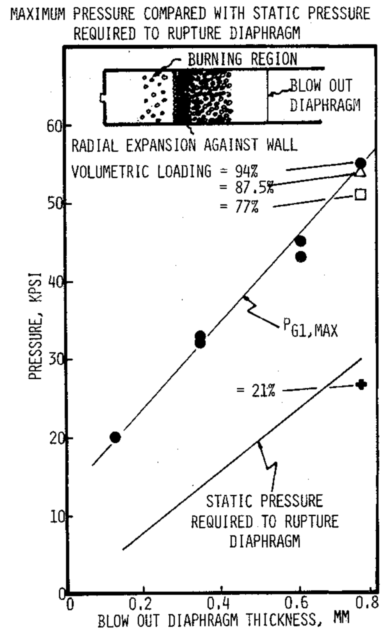

Fig.7 Comparison of $p_{G1,max}$ with static pressure required to rupture diaphragm showing transmission of thrust to the end wall is greatly attenuated. (Combustor was vertical with primer at the top.)

where t_{rs} = defined in Fig. 6, msec; V_u = ullage, cm^3; m_{pr} = mass of the propellant charge of the primer, g; t_{pr} = effective time of primer discharge, msec; K = proportionally constant for a particular primer/propellant configuration, g/cm^3.

Utilizing the $p(x,t)$ data and primer mass flow rate specifications, the value of K is approxiamtely 0.3 g/cm^3. The above relationship, although approximate, offers a direct method of relating ignition delay to primer output and volumetric loading.

From Fig. 5 the pressurization period t_{rp} is seen to be independent of ullage. It therefore depends primarily on the propellant bed characteristics.

Figure 6 shows the effect of combustor axis orientation on the time required for the pressure at G1 to reach maximum. The most rapid pressurization occurs when the primer fires upwards through the propellant bed, i.e., the propellant bed is in physical contact with the primer discharge port and the ullage is on top of the propellant bed. This is consistent with the observations of the effect of ullage on the characteristic times described above. As the ullage volume approaches zero, the orientation effect is negligible.

Table 2 Comparison of the FED 200 and FA 41 primers, showing that FED 200 produced more repeatable ignition transient

Propellant:			WC 846		
Combustor position:			Vertical, primer at top		
Ullage:			0.15 cm^3		
Primer FED 200			Primer FA 41		
Test No.	$t_{G1,max}$ [a] (msec)	Δm_{primer} [b] (g)	Test No.	$t_{G1,max}$ (msec)	Δm_{primer} (g)
35	0.55	....	69	0.56	0.0234
36	0.59	....	70	0.46	0.0201
36	0.59	....	71	0.59	0.0226
		....	72	0.70	0.0211
76	0.64	0.0246	73	0.57	0.0236
75	0.63	0.0257	74	0.65	0.0221

[a] $t_{G1,max}$ is time from first pressure rise of G1 to maximum pressure.
[b] Δm_{primer} is difference in primer mass before and after test.

A study of the variability of primers is shown on Table 2. Two types of primer were used, a special Frankford Arsenal primer FA41 and a commercially available primer FED 200 (manufactured by the Federal Cartridge Corp., Minneapolis, Minn.). The FED 200 is shown to be more repeatable than the FA41. However no correlation was observed between the mass discharge from the primer and t_{GI}.

To investigate the possible attenuation of combustion generated pressure forces transmitted through the propellant bed to the end wall (i.e., to the blow-out diaphragm), tests were conducted over a range of blow-out diaphragm thicknesses. Thus, the maximum pressure which can be maintained at the downstream end was varied. These results show that the time required for G1 to reach maximum pressure, t_{G1}, is (within the experimental variation, $\pm 7\%$) nearly insensitive to the rupture strength of the blow-out diaphragm, whereas the maximum pressure attained varies directly with the blow-out diaphragm thickness (see Fig. 7). A comparison of the rupture strength of the blow-out diaphragm and $p_{G1,max}$ (Fig. 7) indicates that the attenuation of the pressure forces acting on the propellant bed is a very significant effect. In the limiting case of no attenuation, assuming neglible inertia of the propellant mass, the $p_{G1,max}$ curve should nearly coincide with the diaphragm rupture strength curve on Fig. 7. On the other hand, in the other limiting case of total attenuation, the maximum pressure at G1 should be nearly independent of the blow-out diaphragm thickness. Due to the extremely rapid rise of gas pressure in the downstream end of the combustor immediately preceding blow-out (as predicted by the KVS model), the changes in time t_{G1} corresponding to changes in the pressure at which the blow diaphragm ruptures are very difficult to detect.

It is hypothesized that the attenuation is a result of wall friction that results from the pressure gradient deforming the granules in the propellant bed and radially expanding them against the walls of the combustor. At the higher loading densities (e.g., >75%), the action of the primer causes the propellant granules to move downstream and form a column of densely packed propellant. This effect is demonstrated in Fig. 7, which shows that for loading densities of 94, 87.5, and 77%, $p_{G1,max}$ decreases only slightly with increasing loading density (i.e., the granular bed between G1 and the blow-out diaphragm acts as if the downstream region of the chamber is fully loaded). However, for sufficiently low loading density, the granular propellant is not compacted and the pressure in the chamber is nearly uniform (see Fig. 3 and on Fig. 7 compare $p_{G1,max}$ for 21% volumetric loading with the static pressure required to rupture the blow-out diaphragm). The experimental results of Gerri[8,9] reveal that there is an upper limit of granular propellant bed length beyond which the $p(x,t)$ becomes highly unreproducible. To obtain a better understanding of this upper limit Gerri[10] obtained additional information on propellant bed composition by using a downstream section of inert granules in the combustor. Upon examining the inert charge after firing, he found that the leading edge of the section of inert granules was very deformed and radially expanded against the cylinder walls, whereas near the blow-out diaphragm the inert granules were loosely packed. Of course, the present analytical models are not intended for bed lengths beyond which propellant deformation and radial expression of the granular bed completely alter the uniform porosity of the granular bed.

Conclusions

Experimental data have been presented that show the important features of the ignition transients and penetrative burning characteristics of confined granular propellant beds in cylindrical tubes. The most prominent features of the pressure wave are: the gauges along the chamber start to rise in an ordered sequence; the downstream gauges successively overtake the upstream gauges indicating that the maximum pressure occurs within the bed; and after rupture of the diaphragm the expansion wave traveling upstream is sensed by the gauges in an ordered sequence. Thus these measured results verify the 1-D pressure-wave propagation profiles predicted by the analytical models.[1,4-6] Other features of interest include: (a) the ignition time of the granular propellant bed increases sharply with decreasing loading density, whereas the pressurization time is primarily a function of the diameter and burning rate of the propellant granules; (b) wall friction acting on the unburned portion of the propellant along the tube attenuates the downstream transmission of solid phase pressure generated by the upstream combustion process.

The distinct features of the experimental pressure traces obtained in the present work should serve as a guideline for any future theoretical work on the combustion of granular propellant beds and porous propellants. In particular, theory should predict as a function of loading density (a) the pressure wave initiation, (b) the existence of the peak pressure within the granular propellant bed, and (c) the history of the expansion wave after the blow-out diaphragm rupture.

This work has applications to the internal ballistics of guns, studies to understand the deflagration to detonation transition of granular explosives, and the development of porous propellant charges to obtain the ultra-high burning rates required by impulsive thrusters.

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