研究論文

Detonation velocities of single and double base propellants

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The detonation velocity of single base and double base propellants is investigated using two types of ignititor; an exploding bridgewire detonator with C4, and a fuse head with black powder. In the former case, steady-state detonation is achieved and measured, while in the latter case, deflagration-to-detonation transition (DDT) behavior is observed. The detonation velocities of three single base and five double-base propellants are measured, and density correction is applied using KHT and CHEETAH computational code to account for the difficulty in ensuring a constant charge density in the experiments. The diameter effect for single and double base propellants is also determined with respect to the detonation velocity. The calculated detonation velocities at infinite charge diameter are 3624 m·s^{-1} for single base (35I) propellants and 4134 m·s^{-} for double-base (SS) propellants, and the calculated results are shown to be highly consistent with the experimental findings.

KEYWORDS: single base propellants, double base propellants, detonation velocity, smokeless powder, diameter effect

1. Introduction

On August 1, 2000, an explosion occurred at the Taketoyo plant of the NOF Corporation in Aichi prefecture, Japan. The explosion was attributed to 7.7 t of smokeless powder that had been stored at the facility, and resulted in injuries to 79 people and damage to 888 houses in the area[1)]. Based on the report, which detailed the creation of a large crater in the concrete storage facility, the explosives are considered to have detonated rather than undergoing combustion and deflagration. The sequence of event leading to the accident, as indicated by an interim report presented on October 23, 2000 by the investigation committee, is as follows. The smokeless powder, which ages rapidly, was stored in a temporary storage facility for a long period. On the day of the accident, it is thought that the temperature inside the storage facility rose due to solar radiation, which triggered spontaneous ignition and the subsequent explosion.

The present authors have begun to examine the triggers of this accident, starting with the detonation properties in terms of deflagration-to-detonation transition (DDT) behavior and detonation velocity (DV). In this report, we present the results of an investigation into these properties.

Smokeless powder is a ballistic propellant that can be categorized into three forms; single base propellants (SBs), double base propellants (DBs) and triple-base propellants (TBs). The facility in which the accident occurred was used temporarily to store SB and DB, with only a small amount of

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TB. In this study, we are therefore concerned primarily with SB and DB. As these smokeless powders do not generally detonate, we will attempt to determine whether these propellants did in fact detonate, and measure the DV of these propellants. Our detailed investigation of the DDT of various smokeless powders will be presented in another paper.

There has been quite a lot of research recently on stabilizing agents for SB and DB propellants[2,3]. Many solid propellants, although much less sensitive to initiation by shock or other stimuli compared to most high propellants, are detonatable in charge sizes small enough to make storage and handling of such compositions extremely hazardous. There has been some research relating to the DV of SB and DB propellants, and it has been reported that the DV of smokeless powders is not related to the charge diameter, although the accuracy of these measurement is in doubt[4]. In related research, the failure diameter and DV were measured as functions of diameter for several plastisol-nitrocellulose composite propellants, and for ammonium perchlorate and C4 for comparison[5]. It is clear from these studies that the DV is the most important detonation parameter. It is notable that there are very few studies on the properties of smokeless powders. Research related to smokeless powders has been somewhat suppressed in the past because these propellants are used almost exclusively for ammunition and as such are subject to security restrictions.

In this study, the properties of commercial SB and DB propellants are investigated with respect to the variation in steady-state DV with charge radius in a cylindrical geometry (the "diameter effect"). There is a considerable amount of previous research on the diameter effect, specifically relating to composition B[6], high-density heterogeneous explosives[7], ammonium perchlorate[8], and H_2O_2/H_2O mixtures[9].

2. Experimental

Photographs of 35I (SB propellant) and SS (DB propellant) are shown in Fig. 1. 35I is cylindrical, while SS is disc shaped. The shape and internal pore size of smokeless powder differs according to the application in order to achieve a desired burning velocity and ignitability. In this study we examine 5 types of SB propellant and 4 types of DB propellant with respect to the density of propellants and the diameter of the experimental assembly, without paying specific attention to the shape and internal pore size of the materials themselves. Figures 2(a) and (b) show the two experimental assemblies. Type (b) is the BAM standard.

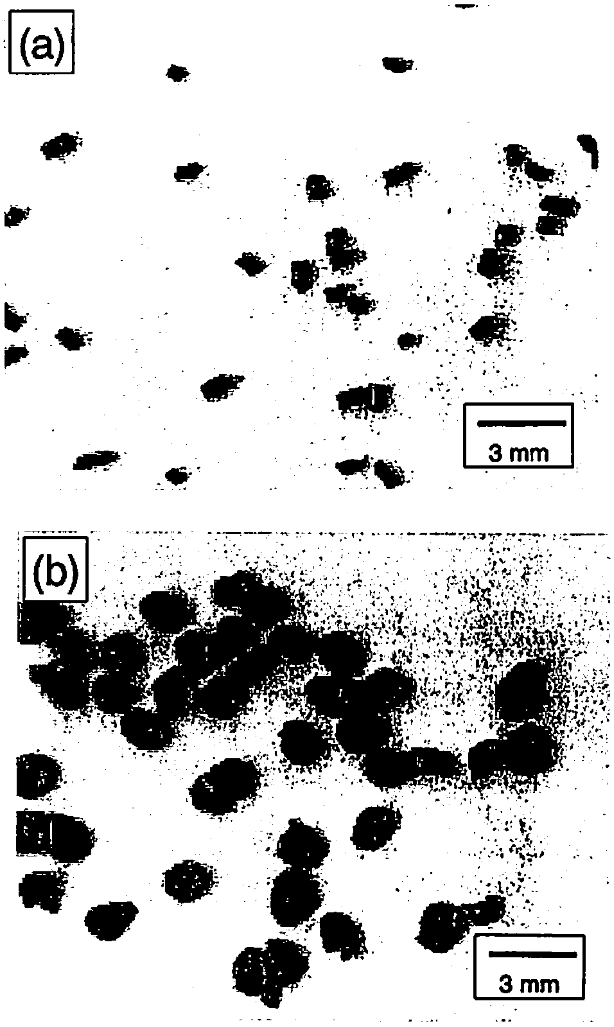

Fig.1 Photographs of (a) single base and (b) double base propellants

Propellants were encased in plain carbon steel tubing as used in the United Nations (UN) DDT test[10]. The regulation steel tubing is G3454 pressure-resistance type. Conventional DV measurement can be made as an average or by continuous measurement. The average method is simple, and is conventionally conducted by the Dautriche method[11], an optical method, or an electrical method. The electrical method is the easiest to perform and gives accurate results, and

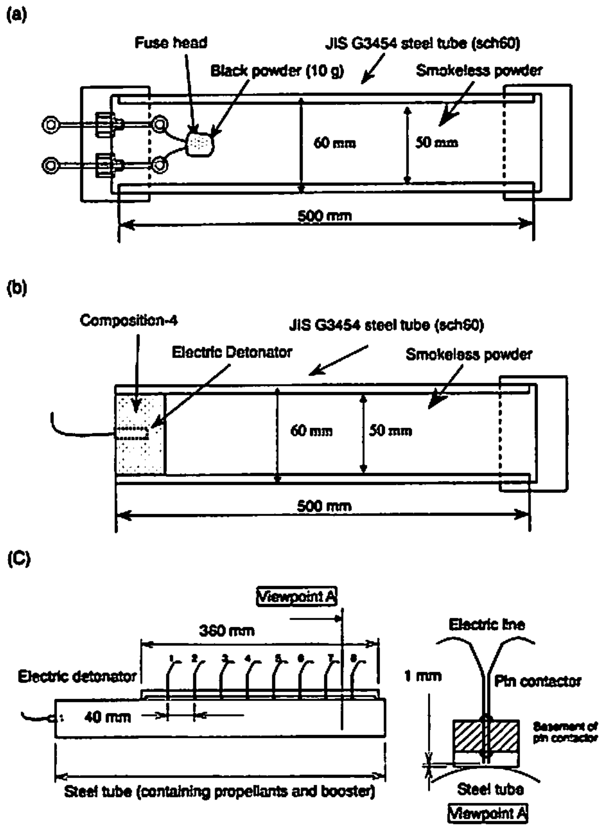

Fig.2 Schematic of charge housing with pin contactor. (a) EBWD+C4 (b) fuse head+black powder (c) pin contactor assembly

can be achieved by ion gap or pin contact approaches. The ion gap method cannot be used efficiently for propellants with high electrical conductivity, as is the case for the smokeless powders examined in this work, which have some degree of conductivity even though 0.2-0.4 wt.% graphite has been introduced to suppress the conductivity. Therefore, the pin contact method is adopted in this work. Figure 2(c) shows a schematic diagram of the steel pipe and pin assembly for measurement of DV.

Two ignition methods were employed to observe the DDT behavior and measure the steady-state DV; a fuse head with 10 g of black powder, or an exploding bridgewire detonator (EBWD; RP-501, Reynolds Industrial Systems, Inc.) with composition-4 (C4). The function time of EBWD is 2.8 + 0.5 μs, and in this experiment was fired by a 4-kV capacitor bank. The variation in DV according to the booster was evaluated.

Three diameters of assembly (ID 27, 35.5 and 55 mm) were examined in order to investigate the diameter effect with respect to the DV. The pin contact assembly (Fig. 2(c)) was fitted to the steel tube. Eight pairs of nickelized steel needles of 1 mm in diameter were attached to a polymethylmethacrylate (PMMA) base attachment. The gap between the pins and the steel tube was 1.0 mm, the distance between pins in a pin pair was 1.5 mm, and the distance between pin pairs was 40 mm. Lengths were measured at 10^{-2} mm accuracy. When the shot is fired, the steel tube deforms, coming into contact with the pins and forming a complete circuit that is recorded via a pulse forming circuit. The pulses were recorded on a transient recorder (RTD-710, Tektronix) at 10 ns resolution.

3. Results and discussion

Figure 3 shows the pin contact for the EBWD+C4 configuration in a 50/60 steel tube. Time zero is the point at which electric current was applied to the EBWD. After a few microseconds, the EBWD was fired. The noise at around 10μs is due to activity of the high-voltage (4 kV) capacitor bank. The pin contacts recorded the procession of the detonation wave, allowing the DV to be calculated precisely. Table 1 shows all the results obtained in this work.

3.1. Effect of different boosters

Figure 4 shows photographs of the fragments of the steel tube after detonation using (a) EBWD+C4 and (b) fuse head+black powder. The EBWD+C4 explosion resulted in relatively uniform, long and thin steel fragments, indicative of steady-state

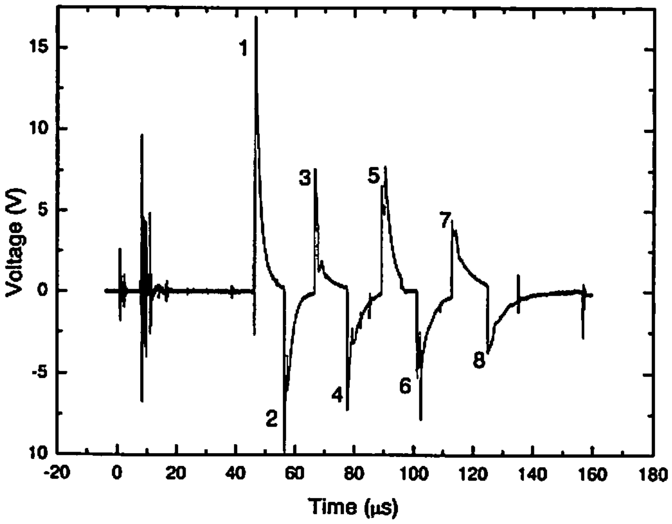

Fig.3 Electrical signal from pin contactor for 35I (DB) with a 50/60 steel tube.

Table 1 Experimentally obtained DVs for single and double base propellants

Type of propellants	Code name	I.D.[*1] (mm)	Amount of propellants (g)	Amount of igniter (g)	Charge desnsity (g/cm^3)	Experimental data		Calculated data			
								KHT		CHEETAH	
						DV(m/s)	R[*2]	DV(m/s)	ΔDV[*3]	DV(m/s)	ΔDV[*3]
Single base	35I	27.0	142.9	23.0	0.513	3515	0.99975	3818	+ 8.6%	3833	+ 9.0%
Single base	35I	27.0	144.8	22.3	0.535	3519	0.99977	3901	+10.9%	3906	+11.0%
Single base	35I	27.0	152.4	22.5	0.563	3587	0.99992	4008	+11.7%	3999	+11.5%
Single base	35I	35.5	235.9	50.8	0.528	3477	0.99979	3875	+11.4%	3882	+11.6%
Single base	35I	50.5	528.8	10[*4]	0.528	3641	0.99855	3875	+ 6.4%	3882	+ 6.6%
Single base	35I	50.5	475.7	140	0.528	3568	0.99950	3875	+ 8.6%	3882	+ 8.8%
Single base	84I	50.5	464.6	145	0.515	3537	0.99915	3804	+ 7.5%	3819	+ 8.0%
Single base	PSB	50.5	425.9	144	0.482	3377	0.99917	3698	+ 9.5%	3726	+10.3%
Single base	18s	50.5	532.7	10[*4]	0.532	3334	0.99593	3868	+16.0%	3926	+17.8%
Single base	NY500	50.5	965.9	10[*4]	0.964	617-1062	0.94383	5306	-	5247	-
Double base	SS	27.0	183.0	14.4	0.659	3924	0.99998	4401	+12.2%	4318	+10.0%
Double base	SS	35.5	300.6	23.5	0.627	3891	0.99999	4279	+10.0%	4212	+ 8.2%
Double base	SS	50.5	568.5	151	0.631	3962	0.99916	4294	+ 8.4%	4259	+ 7.5%
Double base	9P	50.5	595.8	153	0.661	4080	0.99974	4435	+ 8.7%	4399	+ 7.8%
Double base	M9	50.5	685.5	151	0.761	4512	0.99921	4758	+ 5.5%	4681	+ 3.7%
Double base	MJ-B	50.5	573.6	146	0.636	4047	0.99974	4321	+ 6.8%	4290	+ 6.0%
Double base	NP	50.5	579.1	149	0.643	4040	0.99958	4316	+ 6.8%	4276	+ 5.8%

[*1] I.D.=Inner Diamter

[*2] Correlation efficient using least-square fitting

[*3] ΔDV=(Calculated data-Experimental data)/Experimental data

[*4] Using black powder as a ignititer

detonation. The fragments produced by the fuse head+black powder detonation included both short, thick fragments of about 15 cm in length, and long, thin fragments. Based on this observation, the deflagration-to-detonation transition appears to have occurred at about 15 cm from the end of the tube. The same detonation with NY500 propellant had the effect shown in Fig. 4(c), where the steel tube was not significantly fragmented due to a low detonation velocity of 892 to 1062 $m\cdot s^{-1}$, as seen from Fig. 5(c). It is expected that the theoretical DV of 5300 $m\cdot s^{-1}$, as computed using the appropriate code,

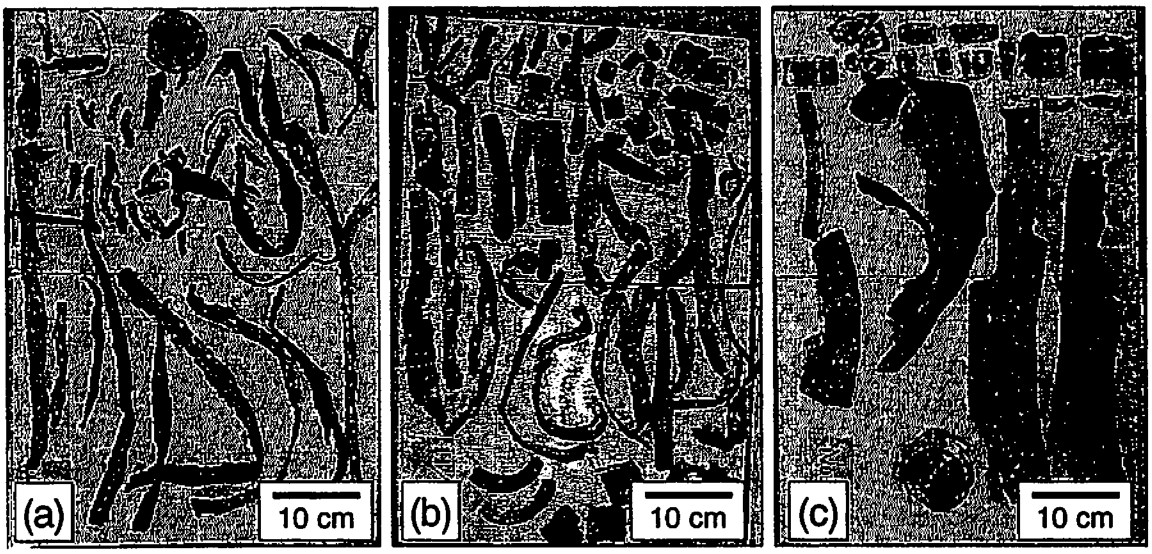

Fig.4 Photographs of steel tube fragments after detonator test for (a) EBWD+C4 with 35I at ρ = 0.528 $g\cdot cm^{-3}$ (b) fuse head+black powder with 35I at ρ = 0.528 $g\cdot cm^{-3}$ (c) fuse head+black powder with NY500 at ρ = 0.964 $g\cdot cm^{-3}$

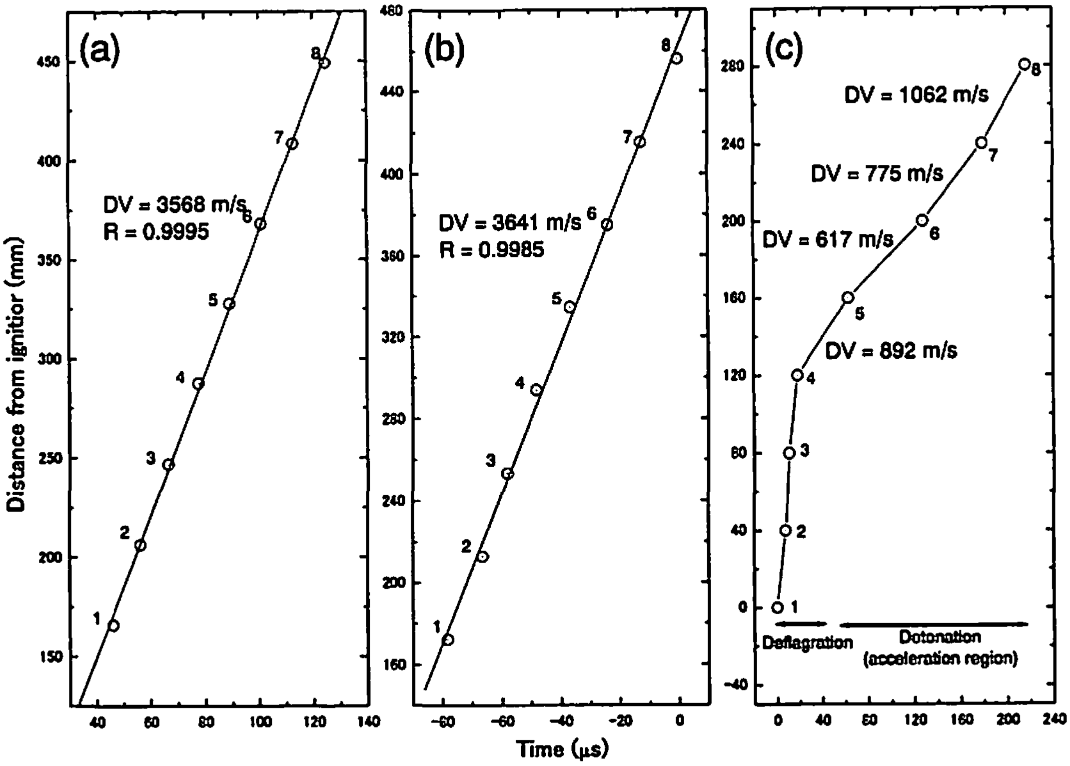

Fig.5 DV measurement (x-t diagram) for(a) EBWD+C4 with 351 at $\rho = 0.528$ g·cm^{-3} (b) fuse head+black powder with 351 at $\rho = 0.528$ g·cm^{-3} (c) fuse head+black powder with NY500 at $\rho = 0.964$ g·cm^{-3}

may be reached if the EBWD+C4 igniter is used with a far longer tube.

Figure 5 shows a DV test using (a) EBWD+C4 and (b) fuse head+black powder. Steady-state detonation appears to be achieved in the earlier stage of detonation using the fuse head+black powder detonator, for which the DV was higher than that for EBWD+C4.

The interval error is ±40μm with respect to each interval of 40 mm, and the time interval error is ± 10 ns, giving a total measurement error of less than ±0.2%. Therefore, the differences in DV are not considered to be due to measurement error, but rather from advance compression of the propellants due to preceding deflagration, which increased the DV for the fuse head and black powder.

In the case of NY500 (SB) with fuse head+black powder detonator (Fig. 5(c)), deflagration occurred between the first and fourth pins, and the steel tube was not fragmented in direct reflection of the wave front. Detonation occurred from the fourth pin, raising the DV from 617 m·s^{-1} to 1062 m·s^{-1}. However, in this case, the speed indicates the rupture speed of steel tube rather than the DV of the smokeless powder. In fact, it is difficult when using the pin contact method to identify exactly whether the measurement indicates the rupture speed of the steel tube or the DV of the smokeless powder under these non-steady-state conditions. Therefore, in order to measure the steady-state DV, we examined EBWD+C4.

Figure 6 shows the relationship between charge density (ρ) and DV. The correlation efficient is 0.983, and the DV is strongly proportional to ρ despite the various diameters, propellants and shapes. In other words, the DV is strongly related to charge density

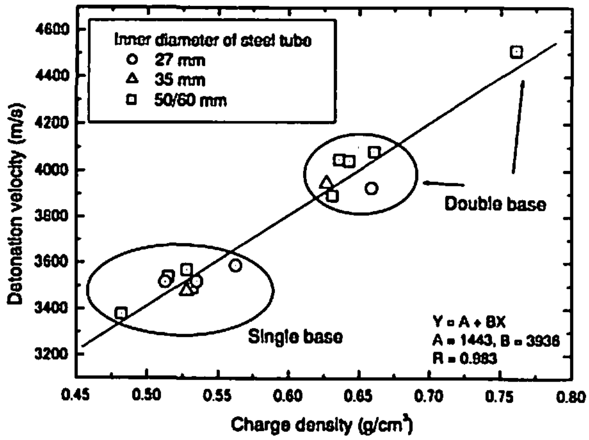

Fig.6 Density dependence of DV for single and double base propellants

rather than other properties such as chemical composition and the inner diameter of the testing tube.

3.2. Density correction using KHT or CHEETAH computational code

As it is difficult to load a consistent amount of propellant in the steel tube, the density dependence of DV was calculated after correction using KHT and CHEETAH computational code. This computation also provides theoretical calculations of the detonation and deflagration properties of pyrotechnic mixtures. The KHT code allows calculation of 900 gaseous and 600 condensed products at high pressure, and the CHEETAH code provides calculations based on the Becker-Kristiakowsky-Wilson equation of state (BKW-EOS) using data from the BKWC and BKWS databases. The BKWC database is composed of only 23 gaseous products and 2 complex products, whereas the BKWS database includes 750 gaseous products and 400 condensed reaction products. If the elemental composition, density, and heat of formation of the propellants and propellants are known, the BKW code can be used to compute C-J equilibrium detonation production composition, C-J pressure, detonation velocity, temperature, the single shock Hugoiniot and isentropy.

A least-squares fit was applied to the experimental results for the DV (Fig. 7). The correlation coefficients (R) are 0.993 and 0.996 for the KHT and CHEETAH codes, indicating that both codes are in good agreement with the experimental data. Density correction was then performed using the slopes calculated from the KHT code, allowing the DV at constant density to be determined. The slope of the experimental results (slope = 3936) was closer to the KHT calculation (slope = 3486) than the CHEETAH calculation (slope = 3236). The experimental results were therefore corrected using the KHT code by fitting a line to the KHT result and translating it to the experimental results while preserving the slope. Engelke et al[9]. introduced this method in order to achieve more accurate estimates of the DV for H_2O_2/H_2O mixtures. To investigate the "diameter effect", we compared the DV at different diameters for the same density of propellant. Figure 8 shows a schematic diagram of the density correction method. The slope of the density calculated using the computational code was used to derive the relationship between DV and charge density from the experimental data. The DV with respect to charge density was then corrected to that of object density.

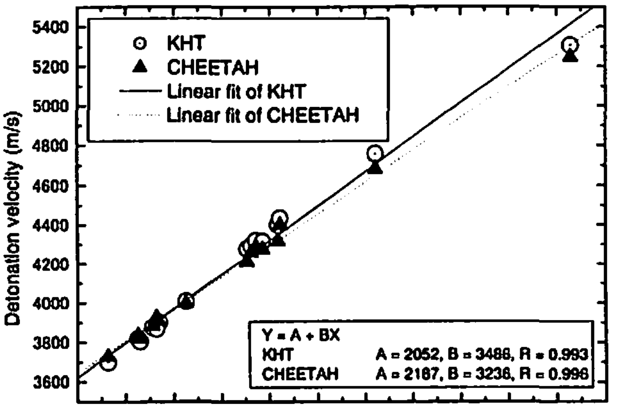

Fig.7 Calculation of DV using KHT and CHEETAH code

3.3. Diameter effect for single and double base propellants

Figure 9 shows the DV diameter effect for single and double base propellants. After density correction using KHT or CHEEETAH code, the DV exhibits a good linear relationship with the reciprocal of the diameter. The limiting DVs for the SB and DB propellants at infinite diameter are 3624 $m \cdot s^{-1}$ and 4134 $m \cdot s^{-1}$, respectively. The experimentally DVs were lower than the calculated values by 7.1% (35I) and 4.1% (SS) for the KHT code, and by 7.1% (35I) and 3.2% (SS) for the CHEETAH

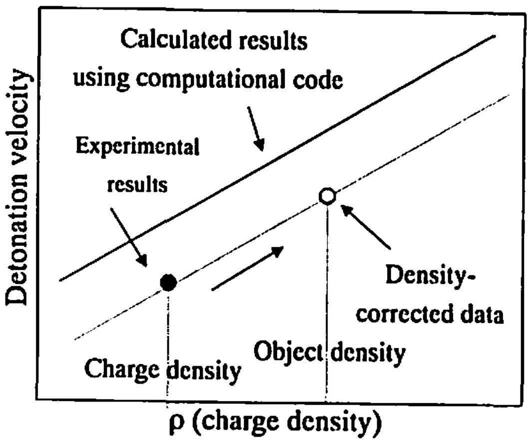

Fig.8 Schematic of density correction method

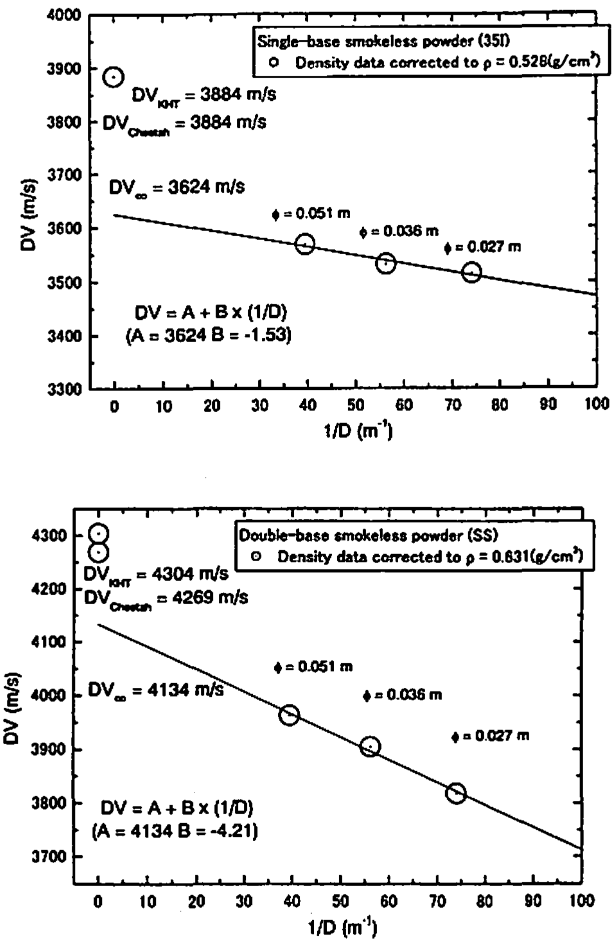

Fig.9 Diameter effect for (a) single base (35I) and (b) double base (SS) propellants

code. Mader[14] reported that the computed and experimental pressures and temperatures agree to within 20% and the DVs to within 10% for such experiments, indicating that our results are very reasonable.

In the comparison between the measured DV and the calculated DV, the following evaluation was introduced. Hobbs et al.[15] and Fried et al.[16] reported the root mean square (*rms*) error between the calculated ($D_{i,c}$) and measured ($D_{i,m}$) detonation velocities as

$$(rms)=\sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(\frac{D_{i,m}-D_{i,c}}{D_{i,m}}\right)^{2}}$$

where the subscripts *i*, m, and c represent the *i*th explosive, and measured and calculated, respectively. *N* represents the number of DV measurements, in this case 14 under steady-state DV conditions. This *rms* definition is generally used to compare calculated and measured values. In Fried et al.[16], an appropriate EOS and parameter was introduced to minimize the *rms* error. However, in the present study, we have only estimated the validity of the calculated values. The measurement error was also estimated by Fried et al.[16]. In the case of a comparison of DVs, the measurement error is considered to be negligible.

Table 2 shows the overall *rms* error for predicting the detonation velocity of the explosives in reference [15] using the BKWS-EOS, BKWC-EOS, JCZS-small, and JCZS-large databases. In this work, the *rms* error of the 14 steady-state DV measurements was 8.8% for CHEETAH and 9.2% for KHT. This is slightly higher than that for Hobbs' results, attributable to the fact that smokeless powder is not a high explosive and contains voids to control the burning velocity. The measured DVs are considered to be in very close agreement with the calculated DVs in this work.

Table 2 Optimized *rms* error

EOS-# of gases	$D^{(a)}$,%	$D^{(b)}$,%
BKWS-132	5.1	5.2
BKWC-22	3.0	2.5
JCZS-44	2.3	2.1
JCZS-132	2.3	2.2

(a) All explosives in ref[16](including nonideal explosives)

(b) All explosives in ref[16] excluding the nonideal explosives containing TATB and HNB

4. Conclusion

Using pressure-resistance steel tube, we found that smokeless powder can be detonated. The various conditions of DV were as follows. The steady-state DV of various propellants, using an exploding bridgewire detonator and C4, was found to be strongly related to the charge density regardless of the type of propellant. Density correction using computational code was effective, and the DVs of single and double base propellants for a charge of infinite diameter were identified as $3624\ m\cdot s^{-1}$ and $4134\ m\cdot s^{-1}$. The computational code produced results that were highly consistent with the experimental results, indicating that the method of DV determination employed in this study is accurate. This study demonstrated that the detonation velocity is a parameter that can be calculated and used in conjunction with other detonation parameter to assist in the prevention and diagnosis of accidents such as that at the NOF facility.

Acknowledgements

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