Detonation Performance of Four Groups of Aluminized Explosives

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Abstract: The detonation performances of TNT-, RDX-, HMX-, and RDX/AP-based aluminized explosives were examined through detonation experiments. The detonation pressure, velocity, and heat of detonation of the four groups of aluminized explosives were measured. Reliability verification was conducted for the experimental results and for those calculated with an empirical formula and the KHT code. The test results on detonation pressures and velocities were in good agreement with the predicted values when aluminum (Al) particles were considered inert. The experimental heat of detonation values exhibited good consistency with the predicted values when a certain proportion of Al particles was active. Ammonium perchlorate (AP) can effectively reduce the detonation pressure and improve the heat of detonation for the RDX/AP-based aluminized explosive. A comparison of the current test results and literature data shows that errors may exist in early test data. The test data presented in this study allow for an improved understanding of the detonation performance of the four groups of aluminized explosives.

Keywords: aluminized explosive, detonation pressure, detonation velocity, heat of detonation, the KHT code

1   Introduction

The detonation performance of explosives has always been a concern for scholars and weapons designers. Detonation performance parameters, such as detonation velocity, detonation pressure and heat of detonation, represent the effectiveness of aluminized explosives. Due to their high combustion enthalpies, aluminum (Al) particles are widely utilized as additives in explosives to increase the reaction temperature, increase the bubble energy in underwater weapons, enhance the air

blast, create incendiary effects and influence warhead performance [1, 2]. These explosives, especially those employed in underwater weapon warheads, are prepared with TNT, RDX, or HMX as the matrix. Ammonium perchlorate (AP) is also added to aluminized explosives as an oxidant, to enhance the oxidizability of the detonation products. The detonation parameters for numerous explosives have been measured and summarized [3, 4], but detonation test data on several aluminized explosives remain lacking. Hence, systematically investigating the detonation performance of different architectures of aluminized explosives is highly necessary.

Aluminized explosives can be classified as non-ideal explosives because they have significantly different detonation properties. A high degree of inhomogeneity and afterburning occurring in the detonation products expanding behind the detonation zone are two important characteristics of aluminized explosives [5]. The size and content of Al particles and the detonation properties of the matrix explosives significantly influence these two characteristics. Thus, many studies have been conducted on the effects of Al particle size and content on the detonation performance and afterburning of aluminized explosives [6-10], to explain the role of Al particles in the detonation process of aluminized explosives, especially the effect of Al particle size on the thermal decomposition of aluminized explosives [11, 12].

Various thermodynamic and detonation parameters can be predicted by thermochemical or hydrodynamic computer codes [13-16], which employ empirical equations of the state of the detonation products [17-19]. To improve the predictions by equilibrium thermodynamics codes, Keshavarz *et al*. [20-23] recently developed several simple empirical relationships, based on experimental data, to predict the detonation pressure for a general $C_aH_bN_cO_dAl_e$ non-ideal explosive. Pei *et al*. [24] also predicted the detonation pressure and velocity through the use of a disequilibrium multiphase model for several aluminized explosives. Nevertheless, highly advanced physics-based models for the prediction of the detonation properties of non-ideal explosives remain lacking.

Although experimental and empirical evidence have revealed the effect of Al particles on the detonation properties of several aluminized explosives, a quantitative assessment of detonation performance cannot be established in the absence of an appropriate experimental strategy for different groups of aluminized explosives. This article presents the experiment methods utilized to measure the detonation pressure, detonation velocity, and heat of detonation of four architectures of aluminized explosives, namely, TNT-, RDX-, HMX-, and RDX/AP-based aluminized explosives. The detonation parameters measured were verified by using empirical relationships and the KHT code.

2 Explosive Specimens

The four groups of aluminized explosives were composed of matrix explosives, Al particles, wax, and graphite (GRPH). The detailed formulas of the four groups of aluminized explosives are shown in Tables 1, 2, 3 and 4. The average molecular formulas of $C_aH_bN_cO_dAl_e$ are provided by assuming one mole of a mixed aluminized explosive with a mass of 100 g, where a, b, c, d and e are the number of moles of carbon, hydrogen, nitrogen, oxygen, and aluminum, respectively. The Al particles mixed in the explosives were grainy and had a diameter of approximately 13 μm. They were not subjected to pre-oxidation treatment and were evenly distributed in the mixed explosives. All cylindrical explosive specimens were pressed and fitted at 250 MPa pressure according to the detonation test requirements for pressure, velocity and heat. The size of each test specimen is shown in Table 5.

Table 1. Formulas of TNT-based aluminized explosives

Formula No.	Al/O	Proportion [wt.%]				ρ [g·cm^{-3}]	Average molecular formula
		TNT	Al	Wax	GRPH		
0	0	100	0	0	0	1.663	$C_7H_5N_3O_6$
1	0	95	0	3	2	1.539	$C_{3.307}H_{2.540}N_{1.255}O_{2.510}$
2	0.165	85	10	3	2	1.573	$C_{2.999}H_{2.319}N_{1.123}O_{2.246}Al_{0.3708}$
3	0.374	75	20	3	2	1.665	$C_{2.691}H_{2.099}N_{0.991}O_{1.981}Al_{0.742}$
4	0.649	65	30	3	2	1.737	$C_{2.382}H_{1.879}N_{0.859}O_{1.717}Al_{1.112}$
5	1.021	55	40	3	2	1.786	$C_{2.074}H_{1.659}N_{0.727}O_{1.453}Al_{1.483}$
6	1.555	45	50	3	2	1.868	$C_{1.766}H_{1.439}N_{0.594}O_{1.119}Al_{1.853}$

Table 2. Formulas of RDX-based aluminized explosives

Formula No.	Al/O	Proportion [wt.%]				ρ [g·cm^{-3}]	Average molecular formula
		RDX	Al	Wax	GRPH		
0	0	100	0	0	0	1.816	$C_3H_6N_6O_6$
1	0	95	0	3	2	1.667	$C_{1.662}H_{3.014}N_{2.566}O_{2.566}$
2	0.162	85	10	3	2	1.720	$C_{1.527}H_{2.744}N_{2.296}O_{2.296}Al_{0.371}$
3	0.366	75	20	3	2	1.788	$C_{1.392}H_{2.474}N_{2.026}O_{2.026}Al_{0.741}$
4	0.633	65	30	3	2	1.853	$C_{1.257}H_{2.204}N_{1.756}O_{1.756}Al_{1.112}$
5	0.998	55	40	3	2	1.921	$C_{1.122}H_{1.933}N_{1.486}O_{1.486}Al_{1.483}$
6	1.526	45	50	3	2	1.989	$C_{0.987}H_{1.663}N_{1.215}O_{1.216}Al_{1.854}$

Table 3. Formulas of HMX-based aluminized explosives

| Formula No. | Al/O | Proportion [wt.%] | | | | ρ [g·cm^{-3}] | Average molecular formula |
		HMX	Al	Wax	GRPH		
0	0	100	0	0	0	1.905	$C_4H_8N_8O_8$
1	0	95	0	3	2	1.721	$C_{1.662}H_{3.014}N_{2.566}O_{2.566}$
2	0.162	85	10	3	2	1.781	$C_{1.527}H_{2.744}N_{2.296}O_{2.296}Al_{0.371}$
3	0.366	75	20	3	2	1.844	$C_{1.392}H_{2.474}N_{2.026}O_{2.026}Al_{0.7416}$
4	0.633	65	30	3	2	1.905	$C_{1.257}H_{2.204}N_{1.756}O_{1.756}Al_{1.112}$
5	0.998	55	40	3	2	1.971	$C_{1.122}H_{1.933}N_{1.486}O_{1.486}Al_{1.483}$
6	1.526	70	50	3	2	2.029	$C_{0.987}H_{1.663}N_{1.215}O_{1.215}Al_{1.854}$

Table 4. Formulas of RDX/AP-based aluminized explosives

| Formula No. | Al/O | Proportion [wt.%] | | | | | ρ [g·cm^{-3}] | Average molecular formula |
		RDX	Al	AP	Wax	GRPH		
1	0.536	20	30	45	3	2	1.959	$C_{0.649}H_{2.520}N_{0.923}O_{2.072}Cl_{0.383}Al_{1.112}$
2	0.684	20	35	40	3	2	1.992	$C_{0.649}H_{2.350}N_{0.881}O_{1.902}Cl_{0.340}Al_{1.298}$
3	0.855	20	40	35	3	2	2.015	$C_{0.649}H_{2.180}N_{0.838}O_{1.732}Cl_{0.298}Al_{1.483}$
4	1.071	20	45	30	3	2	2.041	$C_{0.649}H_{2.010}N_{0.796}O_{1.562}Cl_{0.255}Al_{1.669}$
5	1.331	20	50	25	3	2	2.072	$C_{0.649}H_{1.839}N_{0.753}O_{1.391}Cl_{0.213}Al_{1.854}$
6	1.672	20	55	20	3	2	2.103	$C_{0.649}H_{1.669}N_{0.710}O_{1.221}Cl_{0.170}Al_{2.039}$

Table 5. Experimental specimen size

| Test	Detonation heat	Detonation pressure	Detonation velocity
Specimen size	φ 25 mm × 25 mm	φ 50 mm × 40 mm	φ 40 mm × 40 mm

3 Experimental Methods

The detonation pressures of the aluminized explosives were measured with a manganin high pressure sensor in accordance with the Chinese Military Standard (GJB772A-97 704.2). The arrangement of the experimental setup is shown in Figure 1. When the detonation wave arrives and hits the probe, the manganin sensor begins to record the voltage history because of the resistance

change. The detonation pressure can be obtained by adopting the calibrated relationship between voltage and pressure.
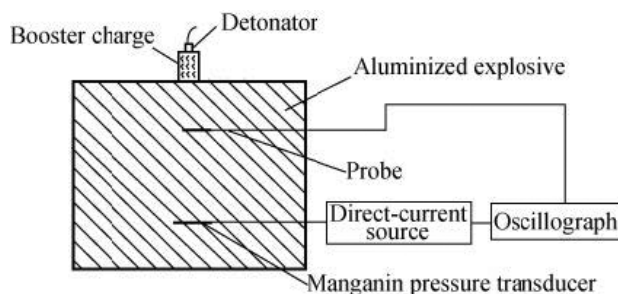
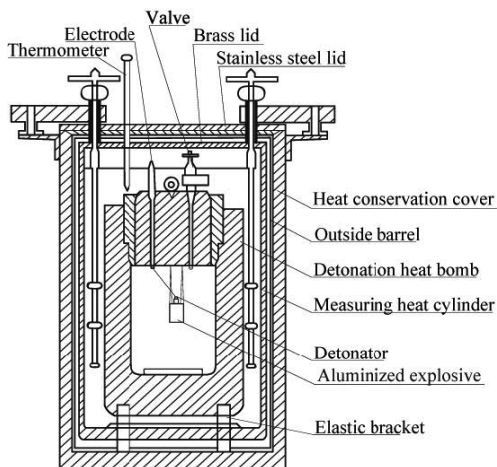**Figure 1.** Scheme for the detonation pressure measurements.

The detonation velocities of the aluminized explosives were measured by the ionization probe method [25] in accordance with the Chinese Military Standard (GJB772A-97 702.1). The experimental arrangement is shown in Figure 2. After detonating the explosives, the detonation wave propagates across four probes in turn (from left to right). The time to traverse the distance between two adjacent probes is recorded by a chronoscope. Thus, the detonation velocity can be calculated in terms of distance and time.
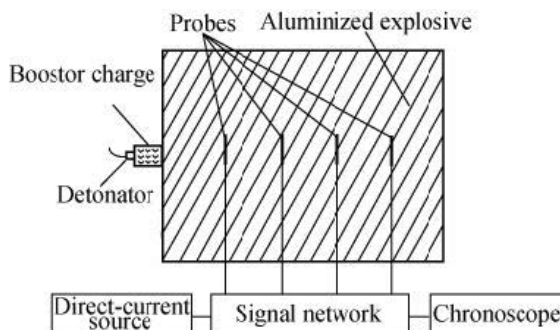
Figure 2. Scheme for the detonation velocity measurements.

The heat of detonation of the aluminized explosives was measured with a detonation heat bomb according to the Chinese Military Standard (GJB772A-97 702.1). A schematic of the experimental arrangement is shown in Figure 3. The detonation heat bomb was evacuated and positioned in a measuring heat cylinder containing 1 kg of distilled water. To obtain the heat of detonation, the stabilized temperatures of the measuring heat cylinder and the outer barrel were

recorded before and after the detonation of the explosive specimens. The heat of detonation can be determined according to the law of conservation of energy.

Figure 3.   Scheme for the heat of detonation measurements.

4   Results and Discussion

The detonation pressure and velocity of aluminized explosives with the general formula $C_aH_bN_cO_dAl_e$ have the following respective empirical formulas [18, 26]:

$$P_{CJ} = -3.5531a + 4.1422b - 1.4770c + 4.4004d - 2.1320e + 4.3950\rho^2 \quad (1)$$
$$D = -582.3a + 233.5b + 97.6c + 304.1d - 1109.0e + 4520.1\rho \quad (2)$$

where P_{CJ} is the detonation pressure in GPa, D is the detonation velocity in m/s, and ρ is the density of the explosive in g/cm³.

The detailed results of the detonation parameters for the four groups of aluminized explosives are summarized in Tables 6-9. The values in the tables are the averages of duplicate test results. The values underlined in the tables indicate that the corresponding method was not applied to the formulas. The measured detonation pressures and velocities were compared with the values estimated by the empirical equation and the KHT code. The Al particles and AP were considered inert ingredients in the prediction of the detonation pressures and velocities with the KHT code.

With a few exceptions, the experimental detonation pressures of the aluminized explosives were lower than the predicted values obtained by

Equation 1 and the KHT code. A large percentage of the deviations, generally attributed to the experimental measurement of detonation pressure (up to 20%), was considered [18]. Given that non-equilibrium effects in the reaction zone may contribute to this confusion, the measured pressures may be smaller than the equilibrium calculations if the measurement is implemented behind the von Neumann spike and in front of the C-J plane. However, the agreement between the calculated and measured pressures is satisfactory. All experimental detonation velocities are consistent with the values predicted by Equation 2 and the KHT code. The maximum deviation was less than 6.5%. This condition indicates that the empirical equations and the KHT code are suitable for estimating the detonation velocity of the mixed aluminized explosives.

As observed in previous studies [8, 27], the heat of detonation of aluminized explosives cannot be accurately predicted with the KHT code unless a certain proportion of the Al particles is assumed to be active ingredients that combust in the detonation products; this view is in agreement with the view of Deiter and Wilmot [25]. However, the KHT code is not an effective method for predicting the heat of detonation of RDX/AP-based aluminized explosives, as shown in Table 8. In the current formulas, when the mass fraction of Al particles exceeds 40%, the KHT code cannot accurately predict the detonation parameters.

The test results show that the heat of detonation of RDX/AP-based aluminum explosives decreases gradually and the detonation pressure and velocity increase with an increase in Al content. These results are different from those of TNT, RDX, and HMX-based aluminized explosives. The differences between groups 1 to 3 and group 4 are mostly due to the property of AP itself. AP is a type of oxygen balance explosive. Its combustion releases heat, improves the oxygen balance of composite explosives and promotes the afterburning reaction of Al particles. However, with a decrease in AP content, composite explosives tend to approach a state of negative oxygen balance, which causes incomplete afterburning reactions and less energy release. Due to the high initiation sensitivity, AP and Al exist on the C-J plane as endothermic inert ingredients and do not participate in the detonation reaction. Given that AP exhibits a higher thermal decomposition temperature than Al, AP absorbs more energy than Al, although AP combusts with the detonation products. Thus, when the mass fraction of RDX remains unchanged and the mass fraction of AP decreases, endothermic inert ingredients decrease and the energy loss on the C-J plane decreases, resulting in increased detonation pressure and velocity. In addition, because of the high heat of combustion of Al, if Al and AP react on the C-J plane, Al would release more energy than AP. Thus, the detonation pressure and velocity increase when the mass fraction of Al increases.

Table 6. Results of the detonation parameters of TNT-based aluminized explosives

No.	P_{CJ}, [GPa]					D, [m·s^{-1}]					Q_v, [kJ·kg^{-1}]		
	Exp.	Eq. (1)	Dev.	KHT	Dev.	Exp.	Eq. (2)	Dev.	KHT	Dev.	Exp.	KHT [a]	Dev.
0	19.10	-	-	19.88	4.1%	6928	-	-	6962	0.5%	4070.0	5262.5	29.3
1	17.95	18.37	2.3%	16.70	-7.0%	6795	6509.5	-4.2%	6575	-3.2%	4154.9	5071.5	22.1
2	16.99	17.26	1.6%	17.60	3.6%	6661	6286.8	-5.6%	6403	-3.9%	4869.6	4909.6	0.8
3	15.18	16.99	12.0%	19.74	30.0%	6575	6326.3	-3.8%	6420	-2.4%	5630.2	5579.7	-0.9
4	15.25	16.50	8.2%	22.31	46.3%	6489	6275.4	-3.3%	7167	10.4%	6392.2	6378.6	-0.2
5	14.17	15.68	10.7%	-	-	6278	6120.5	-2.5%	-	-	7090.1	-	-
6	13.71	15.42	12.5%	-	-	6029	6114.8	1.4%	-	-	6953.2	-	-

[a] The assumption was that 18.9%, 40.5%, and 49.5% of the Al particles are active for formulas 2, 3 and 4, respectively

Table 7. Results of the detonation parameters of RDX-based aluminized explosives

No.	P_{CJ}, [GPa]					D, [m·s^{-1}]					Q_v, [kJ·kg^{-1}]		
	Exp.	Eq. (1)	Dev.	KHT	Dev.	Exp.	Eq. (2)	Dev.	KHT	Dev.	Exp.	KHT [b]	Dev.
0	32.60	-	-	33.39	2.4%	8661	-	-	8696.4	0.4%	5620.0	6206.0	10.4%
1	23.31	26.30	12.8%	26.91	15.4%	8353	8301.9	-0.61%	8066.1	-3.4%	5636.8	5676.5	0.7%
2	22.58	24.87	10.1%	25.77	14.1%	8207	8037.4	-2.07%	7977.8	-2.8%	6205.8	6205.1	0.0%
3	22.04	23.70	7.5%	24.74	12.3%	8087	7840.6	-3.05%	7716.6	-4.6%	6956.3	6909.8	-0.7%
4	20.79	22.52	8.3%	23.36	12.4%	7940	76303	-3.90%	7513.5	-5.4%	7440.8	7448.6	0.1%
5	20.17	21.42	6.2%	26.35	30.6%	7780	7433.5	-4.45%	7351.3	-5.5%	7728.1	7705.7	-0.3%
6	19.21	20.37	6.1%	33.10	72.3%	7460	7236.7	-2.99%	7226.8	-3.1%	7412.3	7412.3	-0.1%

[b] The assumption was that 45.9%, 58.1%, 58.5%, 54.7%, 58.6%, and 45.8% of the Al particles are active for formulas 2, 3, 4, 5 and 6, respectively

Table 8. Results of the detonation parameters of HMX-based aluminized explosives

| No.	P_{CJ}, [GPa]					D, [m·s⁻¹]					Q_v, [kJ·kg⁻¹]		
	Exp.	Eq. (1)	Dev.	KHT [a]	Dev.	Exp.	Eq. (2)	Dev.	KHT [a]	Dev.	Exp.	KHT [c]	Dev.
0	39.00	-	-	38.10	-2.3%	9010	-	-	9091.2	0.9%	5530.0	5987.9	8.3%
1	25.60	27.10	5.86%	29.69	16.0%	8584	8545.9	-0.4%	8223.0	-4.2%	5590.3	5773.3	1.0%
2	24.33	25.80	6.04%	28.69	17.9%	8452	8312.9	-1.7%	8066.4	-4.6%	6173.9	6125.6	-0.8%
3	23.68	24.59	3.84%	26.21	10.7%	8313	8093.6	-2.6%	7897.0	-5.0%	6832.5	6827.7	-0.1%
4	23.14	23.37	0.99%	25.82	11.6%	8141	7865.2	-3.4%	7687.1	-5.6%	7290.5	7319.3	0.4%
5	22.37	22.28	-0.40%	23.98	7.2%	7969	7659.4	-3.9%	7460.2	-6.4%	7267.6	7249.0	-0.3%
6	21.97	21.08	-4.05%	22.26	1.3%	7621	7417.4	-2.7%	7530.6	-1.2%	6985.2	7015.3	0.4%

[c] The assumption was that 47.2%, 58.0%, 56.6%, 49.9%, and 42.8% of the Al particles are active for formulas 2, 3, 4, 5 and 6, respectively

Table 9. Results of the detonation parameters of RDX/AP-based aluminized explosives

No.	P_{CJ}, [GPa]			D, [m·s⁻¹]			Q_v, [kJ·kg⁻¹]		
	Exp.	KHT [d]	Dev.	Exp.	KHT [d]	Dev.	Exp.	KHT [d]	Dev.
1	12.61	14.95	18.6%	6020	5461	-9.3%	8774.4	1122.2	-87.2%
2	13.68	15.22	11.3%	6097	5548	-9.0%	8684.8	1134.6	-86.9%
3	13.83	15.65	13.2%	6176	5575	-9.7%	8441.1	1203.2	-85.7%
4	14.04	-	-	6247	-	-	8054.2	-	-
5	14.26	-	-	6344	-	-	7265.7	-	-
6	14.44	-	-	6400	-	-	6478.1	-	-

[d] The assumption was that the Al particles and AP were inert.

Given that the binder, composed of wax and GRPH, cannot participate in the detonation process, comparing the measured detonation velocities and pressures for several compositions of TNT/Al, RDX/Al and HMX/Al in the current work with those in Reference [28] is essential. The results are shown in Figures 4 and 5. The densities of RDX- and HMX-based aluminized explosives are greater than those of RDX/Al and HMX/Al, whereas the densities of TNT-based aluminized explosives are smaller than those of TNT/Al. When the Al content is the same, the measured detonation velocities for RDX- and HMX-based aluminized explosives are lower than the experimental data for RDX/Al and HMX/Al in [28]. The detonation velocities and pressures of TNT/Al are larger than those of TNT-based aluminized explosives. These results are considered reasonable according to the relations between explosive density and detonation parameters. However, the detonation pressures of RDX-based aluminized explosives are lower than those of RDX/Al. This result indicates that the test detonation pressures in [28] are inaccurate because of the errors of early test technology. Owing to the lack of previously measured data, a comparative study of detonation pressures cannot be conducted for HMX-based aluminized explosives.
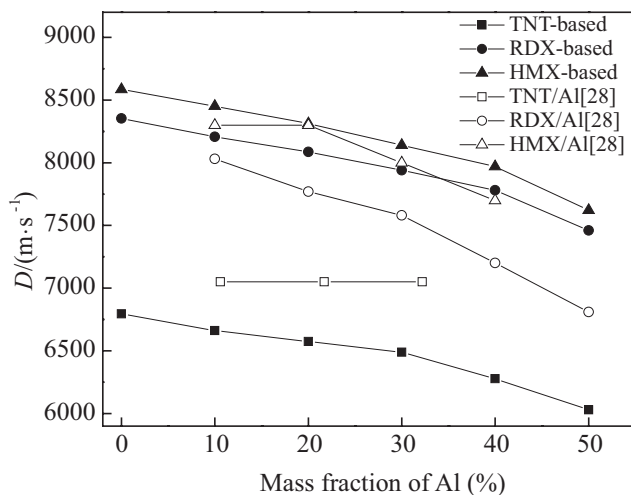

Figure 4. Comparison of detonation velocities between the present results and those in previous literature.

In the present work, the RDX content of RDX/AP-based aluminized explosives is constant at approximately 20%, and the AP content decreases as the Al particle content is increased. Figure 6 shows that the heat of detonation decreases linearly with the increase in the mole ratio of Al particles and AP

(Al/AP). As a positive oxygen balance explosive, AP combustion releases heat, improves the oxygen balance of the composite explosive and promotes the afterburning reaction of the Al particles. However, with the increase in Al/AP, a composite explosive tends to approach a state of negative oxygen balance, which causes incomplete afterburning reaction. This condition results in a decrease in the heat of detonation of composite explosives.
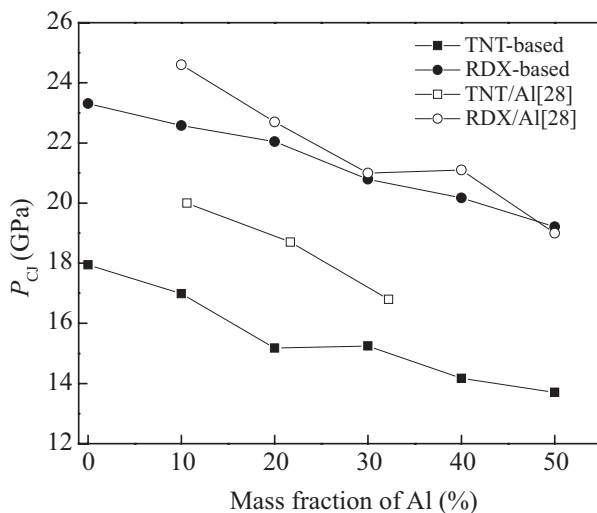
Figure 5. Comparison of detonation pressures from the present results and those in previous literature.
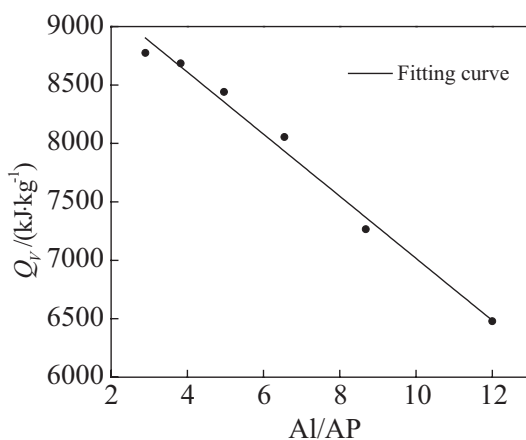
Figure 6. Relation between heat of detonation and the Al/AP ratio for RDX/AP-based aluminized explosives.

5   Conclusions

Detonation experiments were conducted to investigate the performance of four groups of aluminized explosives. Excellent and consistent experimental results were obtained for the detonation pressures and velocities compared with the results calculated by empirical formulas and the KHT code, when Al particles were assumed to be inert. Only when a certain percentage of Al particles was considered to be active could the heat of detonation be accurately predicted. This condition indicates that the afterburning reaction of Al particles provides a significant contribution to the heat of detonation. Furthermore, Al particles do not react completely regardless of how much Al is blended in the explosives. A relatively small effect on RDX-based and HMX-based aluminized explosives is generated when the Al content is equal to approximately 20%. The differences between groups 1 to 3 and group 4 are mostly due to the properties of AP itself, that is, higher initiation sensitivity compared with RDX, a higher thermal decomposition temperature and a low heat of combustion compared with Al. Comparative analysis shows that errors possibly exist in early test data for detonation pressure. The heat of detonation decreased linearly when the Al/AP ratio was increased in the RDX/AP-based aluminized explosive. AP improves the oxygen balance of explosives and promotes the afterburning reaction of Al particles. However, this work lacks detail on the chemical kinetics of afterburning and underwater explosion tests, which will be studied in the future.

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