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Research Article

Effect of Aluminum Powder Content on Air Blast Performance of RDX-Based Explosive Grenade Charge

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For aluminized explosive, the charge performance of explosive grenade is very significant for promoting their application. Firstly, the detonation performance of cyclotrimethylenetrinitramine (RDX) based explosives with different aluminum powder (0%, 20%, 25%, 30%, 35%, and 40%, respectively) content was investigated. Next, the air blast tests of RDX-based aluminized explosives were carried out. Then, RDX-based explosive grenade charges of L-1 and L-2 where the aluminum powder content was 20% and 25% were selected for air blast and static blasting fragments velocity tests. Finally, the energy release mechanism of the air blast was deduced via calculation. The results show that RDX-based aluminized explosives have higher detonation heat, detonation velocity, and detonation volume when the aluminum powder content is 20%, and the shock wave over pressure as well as impulse keep a high level at the same time within 4.5 m. The air blast performance of L-1 is better than L-2 within 2.2 m. As the distance increases, the air blast energy of L-1 is mainly used for shell rupture and fragment acceleration, while the contribution of L-2 is less than that of L-1. This study demonstrated that the explosion power of RDX-based explosive grenade charge is the most powerful where the content of aluminum powder is about 20%.

1. Introduction

Since metal powder with high calorific value (e.g., Al, Mg, etc.) can further release a large amount of energy with the explosive products (e.g., H_2O and CO_2), adding metal powder to the explosive is one of the effective methods to improve the energy of the explosive, which is called metalized explosive [1–3]. Aluminum powder, a commonly used fuel additive with low cost and high energy density, is widely used to increase the calorimetric heat of explosion and expansion work of aluminized explosive [4–9]. Moreover, adding aluminum powder to the explosive within a certain range can provide energy upon the shock wave energy and bubble energy for the underwater explosion [10, 11]. The weight content, particle size, particle distribution, and particle morphology of aluminum can have a great influence on the detonation performance of aluminized explosives [12–19]. Trzciński et al. [14] carried out the effect of aluminum content and of its particle size on detonation characteristics of RDX-based aluminized explosives, and the results showed that when the Al content was 15%, the explosive had better detonation performance. Wang et al. [20, 21] studied the performance of aluminized explosives based on the particle size, shape, and explosive environment of aluminum powder, revealing the role and influence of aluminum powder. Feng et al. [22]studied the effect of aluminum powder content and particle size on the air blast performances of cyclotetramethylenetetranitramine (HMX) based explosives.

Although many studies have been done on the effect of aluminum powder on the detonation performance of aluminized explosive, there are few studies on the charging performance of aluminized explosive grenade. The charge performance and energy release mechanism of aluminized explosive grenade are very significant for the application of aluminized explosives. Thus, in this work, the detonation performance and air blast performance of RDX-based explosives with different aluminum powder content were tested, respectively. Based on the above results analysis, RDX-based explosive grenade charges with different aluminum powder content were studied intensively, and energy release mechanism was deduced, correspondingly.

2. Experimental Section

2.1. Materials and Explosive Formula. Materials: RDX is produced by Gansu Yinguang Chemical Industry Group Co., Ltd., with a particle size of 130 μm. The type of aluminum is FLQT-4, and the particle size is 4~5 μm. The binder is ethylene vinylacetate copolymer (EVA).

Explosive formula: the aluminum powder content is 20, 25, 30, 35, and 40%, respectively. The binder content is 5%, and the RDX content is75, 70, 65, 60, and 55%, respectively.

Preparation of explosive samples: the binder was solved, and the RDX and other components were mixed with the solvent. The mixture was stirred for solvent evaporation. Then, the residuals were screened by sifter with mesh number of 10 and put into a vacuum oven at 50°C for 24 h.

Sample molding: the powders were placed in the certain mould with cylindrical bore, and the sample molding condition was defined according to the sample density values.

Explosive grenade charge: the compressed explosives are directly loaded into the 45# steel cylindrical shell that the diameter and height are 100 and 250.20 mm, respectively. The mass of the explosive charge and the shell material are 3.2 kg and 17.16 kg, respectively. Figure 1 is the schematic diagram of the preparation process of explosive grenade charges.

2.2. Explosive Detonation Parameters Test

2.2.1. The Detonation Heat Test. Firstly, the calorimetric standard material benzoic acid with known calorific value is used to measure the heat capacity of the detonation calorimeter. Secondly, the sample is assembled into a detonation calorimeter. Then, close the cover and vacuum until the pressure is not greater than −0.095 MPa; next, slowly fill the nitrogen to 1.0–1.5 MPa; after checking the tightness, evacuate the nitrogen to the pressure not greater than −0.095 MPa, and repeat twice. Next, using the 8# detonator to detonate the sample, and measuring the temperature rise of the distilled water in the barrel of the detonation calorimeter. Finally, according to the heat capacity and temperature rise value of the calorimeter, the detonation heat is calculated as follows:

$$Q = \frac{C\Delta T_e - q_e}{m}, \tag{1}$$

where Q is the detonation heat of the sample, C is the heat capacity of the detonation calorimeter, $\triangle T_e$ is the temperature rise value, q_e is the detonation heat value of the detonator, and m is the sample mass.

2.2.2. The Detonation Velocity Test. The method 702.1 of GJB772A-97 was used to test the detonation velocity [23]. Based on the characteristics of ionization and conductivity of detonation wave front, the detonation wave propagation time in a certain length of grain is measured using a TSN632M32 channel detonation velocity meter, and the detonation velocity of explosive is calculated. There are 7 samples in each group, and the average detonation velocity is regarded as the detonation velocity of explosives. The assembly diagram of explosives grain is shown in Figure 2.

2.2.3. The Detonation Volume Test. According to the pressure and temperature of the detonation product of the sample in a certain volume of the explosion bomb in a vacuum environment, the ideal gas state equation ($PV = nRT$) is used to calculate the volume of the gas explosion product (*V1*) which excludes water vapor after cooling. Then, the mass of water in the product is measured and converted it to the volume (*V2*) of water vapor in the standard state. The sum of *V1* and *V2* is the detonation volume (V) of the sample.

2.3. Air Blast Test

2.3.1. Instrument. The instruments used are as follows: American PCB company Kistler wall pressure sensor, Chengdu Huatai HC-1210 multichannel waveform recorder, 50 Ω low-noise cable.

2.3.2. Test Layout. RDX-based aluminized explosives: the explosion height is 1.5 m, and the horizontal distances between the wall pressure sensor and the explosives are 1.2, 1.8, 2.4, 3.0, 4.5 m, respectively. Figure 3 is the schematic diagram of the air blast layout.

RDX-based aluminized explosive grenade charges: the explosion height is 1.5 m, and the horizontal distances between the wall pressure sensor and the charges are 2.2, 5.0, 7.5, and 10.3 m, respectively.

3. Results and Discussion

3.1. Detonation Performance of RDX-Based Aluminized Explosives. The detonation heat, detonation velocity, and detonation volume of RDX-based explosives with different aluminum powder content are presented in Table 1.

Table 1 shows that the detonation heat is on the rise with the increase of aluminum powder content. The detonation heat reaches the maximum when the content of aluminum powder is about 35%. However, with the continuous increase of aluminum powder content, the detonation heat presents a downward trend. That is due to the exothermic of aluminum powder and explosive products through the secondary oxidation reaction. When the energy released via the oxidation of aluminum powder is higher than the energy released via the detonation of explosive replaced by aluminum powder, the detonation heat of aluminized explosives will increase. As the content of aluminum powder increases, until the oxygen contained in the explosive is completely consumed, the excess aluminum powder will no longer undergo oxidation reaction to exothermic, so the detonation heat of aluminized explosives shows a downward trend. In addition, with the content of aluminum powder

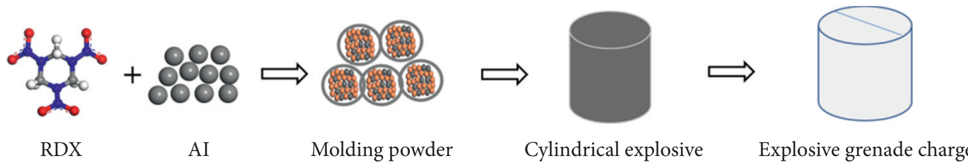

FIGURE 1: Schematic diagram of the preparation process of explosive grenade charges.

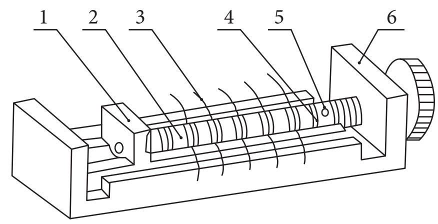

FIGURE 2: Schematic diagram of explosive assembly. 1 is wooden trough, 2 is explosive grain, 3 is probe, 4 is sponge pad, 5 is wooden column, and 6 is jacking press.

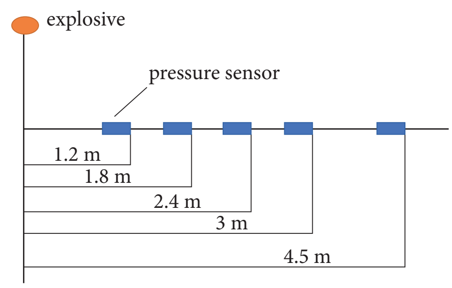

FIGURE 3: Schematic diagram of air blast layout.

TABLE 1: The detonation performance of RDX-based explosives with different aluminum powder content.

Al powder content, %	Standards, mm	Density, g·cm^{-3}	Detonation heat, J·g^{-1}	Detonation velocity, m·s^{-1}	Detonation volume, L·kg^{-1}
0	Φ60 mm × 60 mm	1.68	6190	8800	734
20	Φ60 mm × 60 mm	1.75	6933	8087	659
25	Φ60 mm × 60 mm	1.78	7192	7903	633
30	Φ60 mm × 60 mm	1.81	7451	7840	602
35	Φ60 mm × 60 mm	1.85	7924	7760	535
40	Φ60 mm × 60 mm	1.88	7863	7566	456

increase and the decrease of the RDX explosive content as well as gas products produced by detonation, the detonation velocity and detonation volume will decrease. The detonation velocity is highest (8800 m·s^{-1}) where the aluminum powder content is 0%. While within the range of aluminum powder content of 20~30%, the detonation velocity almost has no decrease. When the aluminum powder content is greater than 30%, the detonation velocity begins to decrease significantly. Because the RDX-based explosive has a high detonation velocity, and its reaction velocity is faster than that of micron aluminum powder. During the detonation of the RDX-based explosive, the aluminum powder does not or rarely participate in the reaction of the Chapman–Jouguet (C–J) front and acts as an inert substance, even absorbing and consuming part of the heat, thereby reducing the total energy of the detonation wave.

The results show that RDX-based aluminized explosives have higher detonation heat, detonation volume, and detonation velocity at the same time where the aluminum powder content is 20%. Therefore, it can be inferred that it has a higher energy output and a stronger working capacity before and after the detonation reaction zone.

3.2. Air Blast Performance of RDX-Based Aluminized Explosives. The damage effect and degree of the detonation shock wave on the target are generally assessed via measuring the shock wave overpressure, positive pressure time, and impulse. The shock wave overpressure, impulse, and positive pressure time of RDX-based aluminized explosives at distances of 1.2, 1.8, 2.4, 3.0, and 4.5 m, respectively, from the explosion center were measured, and the results are presented in Table 2 and Figure 4.

Table 2: Air blast performance of RDX-based aluminized explosives with different aluminum powder content.

Al powder content, %	Air blast performance	Distance to explosion center, m				
		1.2	1.8	2.4	3.0	4.5
20	Overpressure (MPa)	0.97	0.54	0.32	0.19	0.092
	Impulse (MPa·s)	225	200	146	111	87
	Positive pressure time (ms)	0.8	1.2	1.2	1.6	3.2
25	Overpressure (MPa)	0.86	0.49	0.31	0.19	0.085
	Impulse (MPa·s)	219	191	147	114	87
	Positive pressure time (ms)	0.8	1.3	1.4	1.8	3.5
30	Overpressure (MPa)	0.84	0.47	0.29	0.18	0.083
	Impulse (MPa·s)	220	196	146	115	85
	Positive pressure (ms)	0.8	1.1	1.3	1.9	3.1
35	Overpressure (MPa)	0.83	0.45	0.29	0.19	0.079
	Impulse (MPa·s)	214	188	146	116	84
	Positive pressure time (ms)	0.7	1.0	1.3	1.9	3.1
40	Overpressure (MPa)	0.75	0.43	0.27	0.18	0.081
	Impulse (MPa·s)	168	157	130	106	80
	Positive pressure time (ms)	0.8	1.2	1.2	1.7	3.0

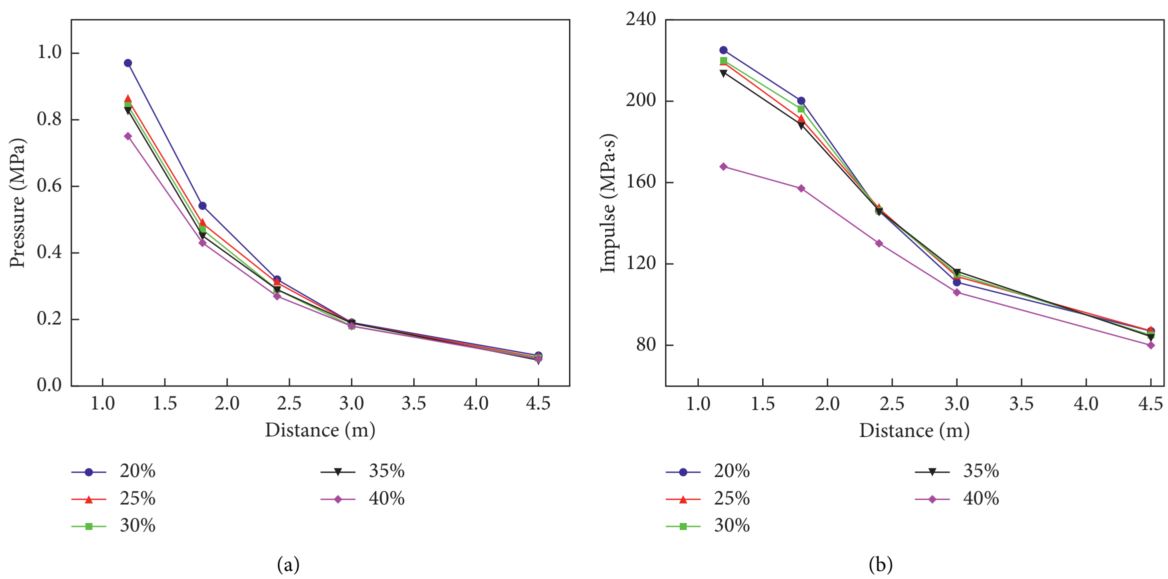

Figure 4: The relationship of the shock wave overpressure, impulse, and distance of RDX-based aluminized explosives. (a) Shock wave overpressure. (b) Impulse.

For the RDX-based aluminized explosive, Table 2 and Figure 4 show that, with the increasing distance, the shock wave overpressure and impulse of RDX-based explosives with different aluminum powder content attenuate rapidly, and the attenuation speed of the low aluminum powder content is faster. At 4.5 m, the shock wave overpressure and impulse drops to about 0.08 MPa and 85 MPa, respectively. A comparison of air blast performance of RDX-based aluminized explosives shows that when the aluminum powder content is 20%, the shock wave overpressure and impulse are the highest, and they maintain high level within the range of 1.2~4.5 m. The shock wave overpressure and impulse almost do not decrease where the aluminum powder contents are in the range of 25~30%. As the aluminum powder content increases to 35%, the shock wave overpressure and impulse present a downward trend. This is because only part of the aluminum powder participates in the reaction, and the excess aluminum powder will be endothermic and consume part of the energy, which will eventually decrease the energy of the detonation wave.

Generally, the detonation velocity is high and the energy transferred to the shock wave is large, which will produce a high initial shock wave overpressure. This is consistent with the fact that RDX-based aluminized explosives have higher initial shock wave overpressure and impulse where the aluminum powder content is 20% in this study. In addition, the initial shock wave attenuates exponentially when the propagation distance increases [24]. When the distance is greater than ten times the diameter of the charge, the shock wave overpressure attenuation speed of the explosive is less than the aluminized explosive which has a subsequent secondary reaction to rise in the amount of explosion energy.

Table 3: Air blast performance of RDX-based aluminized explosive grenade charges.

Samples	Al powder content, %	Air blast performance	Distance to explosion center, m			
			2.2	5.0	7.5	10.3
L-1	20	Overpressure (MPa)	0.377	0.108	0.038	0.027
		Impulse (MPa·s)	176.2	88.8	57.7	40.2
		Positive pressure time (ms)	1.7	5.0	10.5	16.8
L-2	25	Overpressure (MPa)	0.364	0.118	0.055	0.028
		Impulse (MPa·s)	171.9	92.1	64.5	41.9
		Positive pressure time (ms)	1.6	5.1	10.6	16.9

Table 4: Static blasting fragments velocity of RDX-based explosive grenade charges with different aluminum powder content.

Samples	Al powder content, %	Fragment velocity, $m \cdot s^{-1}$	
		4.0 m	6.0 m
L-1	20	1427.5	1318.5
L-2	25	1382.0	1286.0

This is cause of the shock wave of explosives with high aluminum powder content attenuates slowly. Thus, it can be concluded that the RDX-based explosive has a higher initial energy where the aluminum powder content is 20%, and when the aluminum powder content is 25%, the energy attenuates more slowly.

3.3. Performance of RDX-Based Aluminized Explosive Grenade Charges. According to the above results of detonation performance and air blast performance of RDX-based aluminized explosives, RDX-based explosives with aluminum powder content of 20% and 25% (L-1 and L-2, respectively) were selected to complete the grenade charging. Then, the air blast tests were carried out and the static blasting fragments velocity of RDX-based aluminized explosive grenade charges were measured. The results are shown in Tables 3 and 4.

As seen in Table 3, the shock wave overpressure, impulse, and positive pressure time of L-1 are higher than L-2 at the distance of 2.2 m. While the distance is between 5.0 m and 10.3 m, the shock wave overpressure and impulse of L-1 are lower than L-2. The results of Table 4 show that the fragments velocity of L-1 is faster than that of L-2 within 6.0 m. It can be considered that the endothermic effect of aluminum powder on the detonation wave front caused the lower detonation velocity of L-2. The rapid reaction velocity of L-1 releases a higher initial energy, so it has higher shock wave overpressure and impulse within 2.2 m. In addition, it also indicates that when the aluminum powder is 20%, the oxidizing substances (e.g., H_2O, CO, and CO_2) produced by RDX detonation were consumed over via a secondary reaction with the aluminum powder, and the energy release reaches the highest. With the distance increases, the air blast energy of L-1 is mainly used for shell rupture and fragments acceleration, while the contribution of L-2 is less than that of L-1. Therefore, the shock wave overpressure and impulse of L-1 are lower than L-2 at the range of 5.5~10.3 m. Thus, it can be concluded that that the RDX-based aluminized explosive grenade charge is more powerful where aluminum powder content is 20%.

3.4. Mechanism Analysis. The total oxygen oxidation method and the maximum power value method are used to discuss the effect of the amount of aluminum on the RDX-based aluminized explosive formula [25]. The total oxygen oxidation method obtains the theoretically maximum amount of aluminum powder that can be completely oxidized, and the maximum power value method obtains aluminum powder content when the aluminized explosives have the greatest working capability. In the formula, suppose the total mass of the RDX-based aluminized explosive formula is 100 g, the binder content is 5%.

The total oxygen oxidation method believes that all the oxygen contained in the explosive is used to oxidize the aluminum powder to Al_2O_3. The addition of the amount of aluminum powder is calculated via equation (2), and then the theoretical maximum exothermic value is calculated according to Hess's law. The detonation reaction equation is shown in equation (3). After calculation, the content of aluminum powder and RDX in the formula is 32.7% and 62.3%, respectively. Therefore, the theoretical detonation heat via calculated is 15378 $J \cdot g^{-1}$.

$$w_{A1} = \frac{n_{A1} M_{A1}}{n_{A1} M_{A1} + M_{RDX}}, \quad (2)$$

where w_{A1} is the content of aluminum powder, n_{Al} is the amount of the substance that aluminum powder reacts with CO_2 and H_2O, M_{Al} is relative atomic mass of aluminum, and M_{RDX} is relative molecular mass of RDX.

$$C_3H_6N_6O_6 + 4A1^{®}2A1_2O_3 + 3H_2 + 2N_2 + 3C \quad (3)$$

The maximum power value method believes that the CO_2 and H_2O produced by explosives detonation are reduced to CO and H_2 via aluminum powder. The addition of the amount of aluminum powder is calculated via equation (2), and then theoretical detonation heat and detonation volume are calculated. In equation (4), firstly, the carbon in RDX is oxidized to CO, and then the remaining oxygen is evenly distributed for the oxidation of CO and H to CO_2 and H_2O, respectively. Therefore, the amount of CO_2 and H_2O in the product is the same. Finally, the CO_2 and H_2O are reduced via aluminum powder. The detonation reaction equation is shown in equation (5). After calculation, the contents of aluminum powder and RDX in the formula are 19.6% and 75.4%, respectively. The detonation heat and detonation volume are $9357.0\,J\cdot g^{-1}$ and $908\,L\cdot kg^{-1}$, respectively.

$$\begin{aligned} C_3H_6N_6O_6 &\longrightarrow 1.5CO + 1.5CO_2 + 1.5H_2O + 3N_2A1 \\ +1.5CO_2 &\longrightarrow 0.5A1_2O_3 + 1.5COA1 + 1.5H_2O \longrightarrow 0.5A1_20_3 + 1.5H_2 \end{aligned} \tag{4}$$

$$C_3H_6N_60_6 + 2A1 \longrightarrow A1_20_3\text{\_}3CO + 3H_2 + 3N_2 \tag{5}$$

Comparison of the results of the two methods calculated shows that the maximum power value method is consistent with the results of air blast tests. Since the air blast of the explosive grenade charges is expanded via the explosion, and then ruptured and accelerated the shell of the grenade, it is necessary to have high detonation heat as well as detonation volume to achieve a greater work capability.

4. Conclusion

(1) When the aluminum powder content is 20%, RDX-based aluminized explosives have higher detonation heat ($6933\,J\cdot g^{-1}$), detonation volume ($659\,L\cdot kg^{-1}$), and detonation velocity ($8087\,m\cdot s^{-1}$) at the same time, and the overpressure and impulse keep at a high level within a distance of 1.2~4.5 m from the explosion center.

(2) For RDX-based aluminized bare explosives, when the aluminum powder content is 20~25%, the shock wave overpressure and impulse are basically stable; continuous increase in the aluminum powder content, the overpressure and impulse will decrease.

(3) For the RDX-based aluminized explosive grenade charge, the charge containing 20% aluminum powder has a faster explosive reaction rate, which can better complete the fragment acceleration in a longer distance, and the impulse value is still higher.

Data Availability

The data used to support the findings of this study are included within the article. The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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References

[1] X. F. Wang, "Developmental trends in military composite explosive," *Chinese Journal of Explosives and Propellants*, vol. 34, pp. 1–4, 2011.

[2] M. J. Pei, G. W. Mao, H. Q. Hu, and L. Q. Chen, "Characteristic of the thermobaric explosive contained aluminum powders," *Chinese Journal of Energetic Materials*, vol. 15, pp. 441–446, 2007.

[3] M. J. Pei, G. W. Mao, K. W. Zheng, and R. H. Gu, "Explosion performance of thermobaric fuel containing boron," *Chinese Journal of Explosives and Propellants*, vol. 29, pp. 1–5, 2006.

[4] K. Jayaraman, K. V. Anand, D. S. Bhatt, S. R. Chakravarthy, and R. Sarathi, "Production, ccn in composite solid propellants," *Journal of Propulsion and Power*, vol. 25, no. 2, pp. 471–481, 2009.

[5] F. Tepper and G. V. Ivanov, ""Activated" aluminum as a stored energy source for propellants," *International Journal of Energetic Materials and Chemical Propulsion*, vol. 4, pp. 636–645, 1997.

[6] M. C. J. van Ramshorst, G. L. Di Benedetto, W. Duvalois, P. A. Hooijmeijer, and A. E. D. M. van der Heijden, "Investigation of the failure mechanism of HTPB/AP/Al propellant by in-situ uniaxial tensile experimentation in SEM," *Propellants, Explosives, Pyrotechnics*, vol. 41, pp. 700–708, 2016.

[7] R. A. Schaefer and S. M. Nicolich, "Development and evaluation of new high blast explosives," in *Proceedings of the 36th International Annual Conference of ICT*, Karlsrube, Germany, July 2005.

[8] M. A. Cook, A. S. Filler, R. T. Keyes, W. S. Partridge, and W. Ursenbach, "Aluminized explosives," *Journal of Physical Chemistry*, vol. 61, pp. 189–196, 1957.

[9] J. M. Peuker, H. Krier, and N. Glumac, "Particle size and gas environment effects on blast and overpressure enhancement in aluminized explosives," *Proceedings of the Combustion Institute*, vol. 34, pp. 2205–2212, 2013.

[10] E. Stromsoe and S. Eriksen, "Performance of high explosives in underwater applications. part 2: aluminized explosives," *Propellants, Explosives, Pyrotechnics*, vol. 15, pp. 52-53, 1990.

[11] A. Kumar, V. Rao, R. Sinha, and A. S. Rao, "Evaluation of plastic bonded explosive (PBX) formulations based on RDX, aluminum, and HTPB for underwater applications," *Propellants, Explosives, Pyrotechnics*, vol. 35, no. 4, pp. 359–364, 2010.

[12] X. Mao, L. Jiang, C. Zhu, and X. Wang, "Effects of aluminum powder on ignition performance of RDX, HMX, and CL-20 explosives," *Advances in Materials Science and Engineering*, vol. 2018, Article ID 5913216, 8 pages, 2018.

[13] W. A. Trzciński, S. Cudziło, and L. Szymańczyk, "Studies of detonation characteristics of aluminum enriched RDXCompositions," *Propellants, Explosives, Pyrotechnics*, vol. 35, pp. 392–400, 2007.

[14] W. A. Trzciński, S. Cudziło, and J. Paszula, "Study of the effect of additive particle size on non-ideal ExplosivePerformance," *Propellants, Explosives, Pyrotechnics*, vol. 33, pp. 227–235, 2008.

[15] W. M. Howard, L. E. Fried, and P. C. Souers, "Modeling of non-ideal aluminized explosives," *AIP Conference Proceedings*, vol. 505, pp. 389–392, 2000.

[16] X. H. Li, H. B. Pei, X. Zhang, and X. X. Zheng, "Effect of aluminum particle size on the performance of aluminized explosives," *Propellants, Explosives, Pyrotechnics*, vol. 45, pp. 1–8, 2020.

[17] A. K. Mishra, H. Agrawal, and M. Raut, "Effect of aluminum content on detonation velocity and density of emulsion explosives," *Journal of Molecular Modeling*, vol. 25, pp. 2–5, 2019.

[18] M. J. Lin, H. H. Ma, Z. W. Shen, and X. Z. Wan, "Effect of aluminum fiber content on the underwater explosion performance of RDX-based explosives," *Propellants, Explosives, Pyrotechnics*, vol. 39, pp. 230–235, 2014.

[19] F. Jiang, X. F. Wang, Y. F. Huang et al., "Effect of particle gradation of aluminum on the explosion field pressure and temperature of RDX-based explosives in vacuum and air atmosphere," *Defence Technology*, vol. 15, pp. 844–852, 2019.

[20] Y. F. Huang, X. Tian, B. Feng, and X. F. Wang, "Effect of particle size and shape of aluminum powder on the explosion field pressure and temperature of RDX-based explosive in vacuum environment," *Chinese Journal of Energetic Materials*, vol. 24, pp. 144–148, 2016.

[21] X. J. Feng, X. F. Wang, Y. Y. Li, and H. T. Xu, "Effect of aluminum particle size and explosion atmosphere on the energy of explosion of aluminized explosive," *Chinese Journal of Explosives and Propellants*, vol. 36, pp. 24–27, 2013.

[22] X. S. Feng, X. J. Feng, J. Zhao, and X. Tian, "Effect of content and particle size of aluminum powder onthe air blast property of HMX-based explosive," *Explosive Materials*, vol. 47, pp. 10–15, 2018.

[23] X. Yang, K. Zhao, X. Tian et al., "An efficient energy characteristics and explosion heat improving method of FOX-7-based aluminized explosives," *FirePhysChem*, vol. 1, pp. 1–7, 2021.

[24] X. Y. Duan, *Study on the Properties of Shock Wave from Aluminized Explosives Blast in Air*, Beijing Institute of Technology, Beijing, China, 2020.

[25] Y. B. Sun, J. M. Hui, and X. M. Cao, "Military mixed explosive," in *Aluminized Explosive*, pp. 470–475, Weapon Industry Press, Beijing, China, 1995.