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Research Article

Detonation Wave Propagation of Double-Layer Shaped Charge and Its Driving Characteristics to the Liner

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The double-layer charge can effectively improve the axial driving ability of explosives, which shows a considerable engineering application prospect in highly efficient damage warheads. Due to the complex wave structure produced by the overpressure detonation of a double-layer charge, a series of dynamic behaviors inside the shaped charge liner will be affected. By comparing the detonation wave shapes of single-layer charge and double-layer shaped charge structure and the jet shaping parameters of a double-layer shaped charge with different structural parameters, the evolution of detonation wave and the state parameters in the wave system are analyzed in this research. The research found that the double-layer charge with high detonation velocity in the outer layer and low detonation velocity in the inner layer can produce continuous overpressure detonation, which makes the overpressure detonation state be applied efficiently. Meanwhile, this study found that the overpressure detonation field formed by the double-layer charge changes the action law of the traditional single charge on the shaped charge liner. The detonation waveform of the entire charge is controlled by different detonation velocities and detonation energies, and a detonation waveform that matched well with the shaped charge liner is obtained. This study solves the matching relationship between the structure of the overpressure detonation wave system and the properties of a double-layer charge, which is of great value for improving the detonation-driving effect of condensed explosives on surrounding media. The double-layer charge can effectively enhance the potential of explosive charge. It is not only widely used in military fields such as improving the armor-breaking power of shaped charge penetrators and improving the muzzle velocity and concentration of fragments of directional warheads, but also can promote the development of industrial fields such as explosive processing.

1. Introduction

The overpressure detonation of explosives occurs under a strong impact that is beyond the critical initiation condition, and the pressure is higher than the von Neumann peak value in the ZND detonation model. This high-intensity impact process is bound to cause another detonation mode of explosives [1]. Compared with CJ detonation, the overpressure detonation state point is located above the CJ point on the Hugoniot curve. The phenomenon of overpressure detonation is first observed by Altshuler in explosive B. By special experimental means, the detonation velocity is more than twice of CJ detonation velocity, and the overpressure detonation pressure reaches 120 GPa [2].

At present, overpressure detonation can be obtained by means of high-speed flyer impact, Mach reflection between detonation waves, and double-layer charge of high and low detonation velocity explosives. The outer charge adopts a high detonation velocity explosive, which is prior to the inner low detonation velocity explosive. Overpressure detonation is formed in the inner explosive under the strong impact of the detonation products of the outer charge. Because of the particularity of this kind of excitation mode, the state of overpressure detonation can be maintained over a long distance. In recent years, the excitation mode of overpressure detonation has been widely concerned by scholars. The laboratory of material impact dynamics of Kumamoto University in Japan has carried out in-depth research and achieved representative research results. Hamada [3] and Liu et al. [4] used the HEMP program to simulate the action process of explosive overpressure detonation, including double-layer charge and high-speed flyer impact initiation. Hamada et al. [5] set up a test device to test the overpressure detonation, in which the inner explosive is a high-density explosive with different proportions of tungsten powder, and the outer explosive is a high detonation velocity explosive. The plane wave generator is used to obtain the initial detonation waveform, and the detonation pressure and detonation velocity of the inner charge are measured by sensors and optical fiber probes. Kato et al. [6] carried out experimental research on the performance of double-layer charge with high-density explosives as inner charge and obtained the jet head velocity, penetration velocity, and penetration performance of double-layer shaped charge. Zhang and Qiao [7] based on the Lee Tarver model of impact initiation of condensed explosive, numerically simulated the action process of double-layer shaped charge by using AUTODYN finite element calculation software, calculated and analyzed the jet forming and penetration performance of sandwich-shaped charge with different detonation velocity explosive matching relationship. Compared with single structure charge, the jet head velocity and total kinetic energy of double-layer shaped charge have been greatly improved. The double-layer shaped charge can effectively improve the head velocity of shaped metal jets, the penetration depth, and the workability of explosive charge. Hussain et al. [8, 9] compared the difference of jet formation between single charge and double-layer charge by numerical simulation and experimental research and obtained that under some specific conditions, the shaped charge jet formed by single charge is better than that of double-layer charge, which is determined by the matching of overpressure detonation wave waveform and liner structure. Wang et al. [10] used orthogonal multislit scanning technology to measure the detonation waveform of double-layer charge under eccentric initiation conditions, analyzed the propagation characteristics and variation law of overpressure detonation wave, and obtained that the double-layer charge structure can optimize and adjust the detonation waveform. Ha [11] proposed a trailing edge flap system, and the design study was performed to show the equilibrium condition analytically, and the applicability of the new trailing edge flap system for wind turbine blades with regard to the aerodynamic force. Fouad et al. [12] carried out the numerical investigation of RC columns with different reinforcement detailing subjected to near-field explosions. The effect of several modeling parameters was studied such as mesh sensitivity analysis, and the inclusion of air medium and erosion values on the displacements and damage pattern. Ansori et al. [13] numerically investigated the geometrical effects of the sandwich panel on intact and damaged models. The results showed that the hexagonal core was more resistant to blast loads than the square design.

In summary, the double-layer charge structure of high- and low-velocity explosive combinations provides a new way for the development of overpressure detonation. The double-layer charge changes the layout of the traditional single charge and uses the outer high-velocity explosive to take precedence over the inner charge to detonate, and the inner charge forms the overpressure detonation under the strong impact of the detonation product of the outer charge. The advantage of this excitation mode is that the overpressure detonation state can be maintained over a long distance, and this characteristic of overpressure detonation can be used to drive the liner to improve the damage efficiency of the shaped charge penetration body. The key to realizing the improvement of damage element performance is to control the waveform and main characteristic parameters of overpressure detonation. The overpressure detonation of a double-layer charge can effectively improve the potential of an explosive charge. It is of great significance to reveal the formation mechanism and waveform evolution mechanism of overpressure detonation of interlayer charge for improving the detonation theory under different conditions.

Overpressure detonation of a double-layer charge involves two layers of explosives with different properties inside and outside, and there are interface effects such as reflection and transmission in the process of detonation wave propagation. Moreover, since the detonation speed of the outer explosive is higher than that of the inner charge, the overpressure detonation will occur in the inner charge. Finding out the matching relationship between the structure of the overpressure detonation wave, and the properties of the double-layer charge is the key to solving the overpressure detonation mechanism of the double-layer charge. The overpressure detonation field formed by the double-layer charge changes the action law of the traditional single charge on the liner, and the molding problem of the overpressure detonation drive liner needs to be solved urgently. Therefore, it is necessary to carry out the molding research of the overpressure detonation drive liner, which provides the theoretical and technical basis for the development of a new generation of efficient damage technology.

How to adjust and control the overpressure detonation waveform is the core of the superiority of overpressure detonation. In order to avoid the negative effect brought by overpressure and make more reasonable use of double-layer charge to improve the explosive potential, it is necessary to reveal the action law of double-layer charge to form an overpressure detonation wave. This paper will carry out the study of double-layer charge overpressure detonation and its driving effect on the liner from three aspects. First, the layered shaped charge structure is designed and the overpressure detonation propagation process is analyzed. Second, the detonation wave propagation process and jet-forming parameters of single-layer charge and double-layer shaped charge structure under ring initiation are compared, and it is found that the interlayer-shaped charge structure with low detonation velocity inside and high detonation velocity outside can form a better overpressure detonation effect. Finally, the influence laws of overpressure detonation properties and shaped penetration body forming on the cone angle, charge height, and charge radius ratio of inner and outer layers are studied, respectively.

2. Methods

In this study, a double-layer shaped charge structure was first designed. Two kinds of explosives with different detonation speeds were used for the inner and outer layers of charge, respectively. The propagation process of overpressure detonation was numerically simulated and analyzed, and it was found that the explosives with high detonation speed in the outer layer and low detonation speed in the inner layer could form long-distance overpressure detonation. On this basis, five charge structures were designed, including three double-layer charges and two single-layer charges. The differences in detonation wave propagation and jet-forming parameters under different charge types were analyzed, and the evolution law of the angle between the detonation wave front and the axis was obtained. The performance parameters of jet forming and the utilization rate of the liner were compared. Based on the charge type of the inner TNT and the outer B explosive, the influence law of the double-layer charge structure layout on the forming of the overpressure detonation-driven liner was systematically studied. The laws of typical physical quantities such as detonation waveform, the angle between the detonation front and the axis, jet velocity gradient, the utilization rate of the liner, the pressure of the Mach rod, and the density of the Mach reflection overpressure region were obtained. In this study, under the influence of complex factors such as convergence, reflection, and transmission of detonation waves in the process of propagation under the condition of double-layer charge, the matching rule among double-layer charge structure, overpressure detonation waveform, and liner structure is obtained, which effectively improves the shape of overpressure detonation wave and forms a control method that can replace the traditional multipoint initiation to generate overpressure detonation wave. It avoids the problems that the design of a multipoint initiation network needs to consider the initiation deviation, and the initiation accuracy increases exponentially with the increase of charge diameter.

3. Structure Design and Overpressure Detonation Propagation Process of Double-Layer Shaped Charge

3.1. The Structure of Double-Layer Shaped Charge. The structure of the double-layer shaped charge is shown in Figure 1. Considering the symmetry of the model, a 1/2 model is established. The charge radius is R, and the inner charge radius is r. The outer charge thickness is R-r, and the charge height is h. The top charge height of the liner is h, and the liner adopts a conical structure. The top inverted arc radius is R'. In order to ensure the formation of overpressure detonation in the charge, the top ring initiation mode is adopted, and the initiation radius is R.

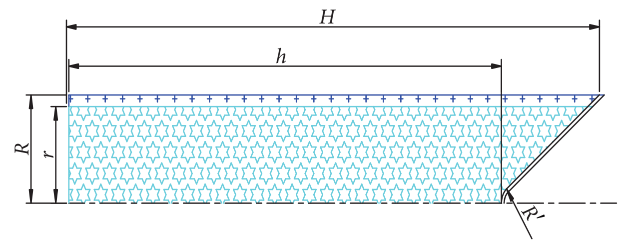

Figure 1: 1/2 model of the double-layer shaped charge.

3.2. Selection of Algorithm and Material Model. The two-dimensional finite element model of double-layer shaped charge is established by using AUTODYN software, as shown in Figure 2. The Euler algorithm is selected, and the JWL equation of state is used for the outer explosive. The Lee-Tarver impact initiation model is used for the inner explosive, and the CU-OFHC model is used for the liner.

3.3. Propagation Process of Overpressure Detonation. In scheme 1, the inner charge is TNT and the outer charge is explosive B. In scheme 2, the inner charge is explosive B and the outer charge is TNT. By setting gauge points on the explosive, the evolution of detonation pressure is analyzed. A gauge point is arranged every 2 cm on the charge axis with an axial distance of 2.2 cm to 18.2 cm from the initiation center. The pressure change of the gauge point on the axis is shown in Figure 3 during the detonation process. *X* is the axial distance from the gauge point to the initiation surface.

It can be seen from Figure 3 that for the double-layer charge with low detonation velocity in the inner layer and high detonation velocity in the outer layer adopted in scheme 1, the detonation pressure of the inner charge occurs obvious overpressure detonation, and the detonation pressure reaches 92.886 GPa at 7.2 cm from the initiation center in the axial direction, and then gradually decreases. The detonation pressure is basically stable at about 46 GPa at 15.2 cm from the initiation center in the axial direction, which can reach 2.19 times the C-J pressure. In scheme 2, the detonation pressure reaches 90.432 GPa at 7.2 cm away from the detonation center, but the pressure drop trend is more obvious. It is basically stable at about 25 GPa at 15.2 cm away from the detonation center, while the C-J pressure of the inner charge is 29.5 GPa.

Because the inner low and outer high double-layer shaped charge can form good overpressure detonation, several typical moments in the process of detonation propagation are analyzed in Figure 4, and then the formation process of overpressure detonation is simply analyzed.

The detonation of the outer charge occurs after initiation, forming the detonation wave in the initial stage. At this moment, the pressure and temperature increase rapidly. The pressure and temperature change in this stage are almost dominated by the chemical energy released by the detonation of the outer charge. The detonation wave gradually propagates to the inner charge, and detonates the inner charge with the Lee Tarver shock initiation model, as shown in Figure 4(a). With the propagation of the detonation wave,

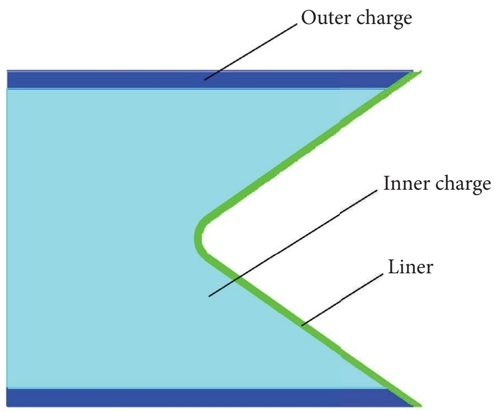

Figure 2: Simulation model.

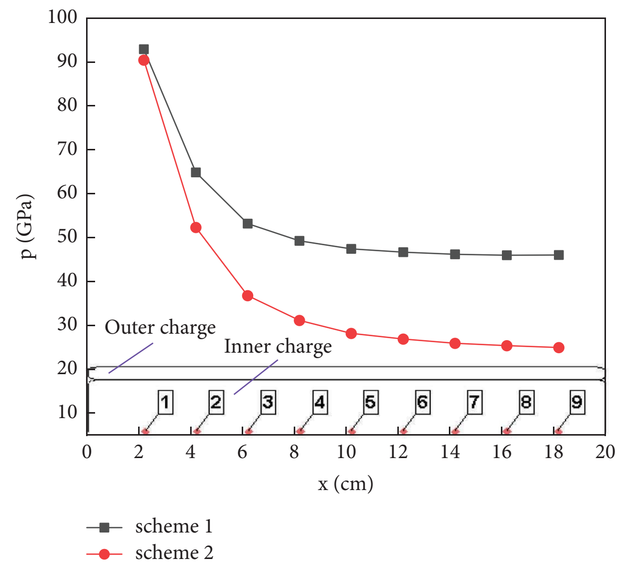

Figure 3: Pressure change of gauge point at the axis.

the detonation products behind the wavefront gradually converge to the center line. The detonation waves on both sides collide at the charge center line and propagate forward at a certain angle after convergence. Under the combined action of detonation wave, explosive, and detonation products, a strong shock wave with extremely high pressure and density is formed at the explosive center line. As shown in Figure 4(c), Mach collision occurs after a certain distance.

4. Comparison of Jet Formed by Single-Layer Charge and Double-Layer Charge

4.1. Simulation Scheme. Based on the AUTODYN software, the detonation wave propagation process of the single-layer charge structure and the double-layer charge structure is compared and analyzed. Meanwhile, the jet forming is numerically simulated, and the detonation wave propagation and jet-forming parameters of the single-layer charge and the double-layer charge structure are analyzed. The scheme design and the explosive material model of different charge structures are shown in Table 1.

4.2. The Propagation Process of Detonation Waves. Figure 5 shows the detonation wave waveforms of the five schemes. In scheme I, with the inner low and outer high double-layer charge, the outer detonation wave always propagates forwards ahead of the inner detonation wave, which has a good adjustment effect on the detonation wave waveform. Compared with the scheme I, the inner and outer layers are loaded in scheme III. The detonation velocity difference of the medicine is larger, and the adjustment effect on the detonation wave is more obvious. In scheme II, the detonation wave of the outer charge will propagate in priority to the detonation wave of the inner charge in the initial stage of the sandwich charge of the inner high and outer low type, which has a certain adjustment effect on the detonation waveform of the double-layer charge. However, the detonation wave of the inner charge has surpassed the detonation wave of the outer charge at 4 μs, and the detonation wave generated by the detonation of the outer charge has no effect on the detonation wave of the double-layer charge. The wavefront gradually became flat at 5 μs. There is almost no difference in the overall change of the detonation waveform of the two single-layer charge structures in scheme IV and scheme V, except that the detonation wave front of scheme V with a higher detonation velocity charge is closer to flat. Comparing the above five schemes, it is not difficult to conclude that the inner-low and the outer-high double-layer charge has the best adjustment ability to detonate waves. The greater the difference in detonation velocity between the inner and outer layers, the more obvious the adjustment effect.

The initiation of the charge can be equivalent to the detonation wave propagation process in Figure 6. During the explosive detonation, the reflection of the detonation wave can be divided into normal oblique reflection and Mach reflection, as shown in Figure 6. Using the ring initiation method, the detonation wave converges at point A of the charge axis, and the angle between the wavefront of the incident wave and the charge axis is β_1. At this moment, the normal oblique reflection occurs. The blast wave continues to propagate forward at a certain angle. When the angle of the incident wave α is more than 44.5°, Mach collision occurs. A strong shock wave with extremely high pressure and energy density is formed at the charge axis. At this moment, the angle between the wavefront and the charge axis $\beta_2>\beta_1$. When the Mach wave propagates to point C, the height of the Mach rod is h, θ is the angle between the tangent m and the straight-line n, where the tangent m is the tangent of the detonation wave front at the apex of the Mach rod., and the straight-line n is the line connecting the point where the Mach collision occurs initially and the apex of the Mach rod at point C.

In order to compare the changes of detonation waveform after the Mach collision more objectively, Figure 7 shows the change curve of angle θ of single-layer charge and double-layer shaped charge with L, where θ is the apex of the Mach rod after the Mach collision. The angle between the tangent m of the incident wavefront,

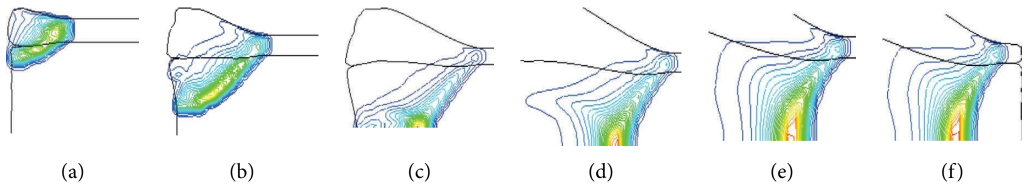

FIGURE 4: Detonation wave propagation of double-layer shaped charge with low inner and high outer: (a) $t = 2\,\mu$s, (b) $t = 4\,\mu$s, (c) $t = 6\,\mu$s, (d) $t = 10\,\mu$s, (e) $t = 20\,\mu$s, and (f) $t = 24\,\mu$s.

TABLE 1: Scheme design of single-layer charge and double-layer charge.

Scheme	Double-layer charge				Single-layer charge	
	Inner charge	State equation	Outer charge	State equation	Charge	State equation
I	TNT	Lee-Tarver	B	JWL	—	—
II	B	Lee-Tarver	TNT	JWL	—	—
III	TNT	Lee-Tarver	CYCLOTOL	JWL	—	—
IV	—	—	—	—	TNT	JWL
V	—	—	—	—	B	JWL

and the line n between the point where the Mach collision occurred initially and the apex of the Mach rod. The smaller θ, the better the adjustment effect on the detonation wave, where L represents the axial distance between the Mach collision point and the detonation center.

The angle θ of the two single-layer charge structures is significantly higher than that of the three double-layer charge structures. The higher the explosive detonation velocity of the single-layer charge structure used, the larger the angle θ, that is, the worse the adjustment of detonation waves. Among the three types of double-layer charges, the inner-low-outer-high-type double-layer shaped charge with a higher detonation velocity in the outer layer has the best effect on detonation wave adjustment, and the inner-low-outer-high-type double-layer charge with a high detonation velocity in the outer layer has the best effect on the adjustment of detonation waves. Second, the inner high-outer low type double-layer shaped charge is the worst. Comparing the L values of the five schemes, it can be seen that the single-layer charge structure generates the convergent detonation earlier than the sandwich charge structure, that is, the single-layer charge structure is more conducive to the formation of convergent detonation waves.

4.3. Jet-Forming Performance. The jet-forming parameters and the velocities of the jet head and tail are shown in Table 2 (30 μs), where V_T is the velocity of the jet head, V_W is the velocity of the jet tail, and L is the length of the jet.

Compared with the scheme (I) the jet head velocity and tail velocity of scheme II are reduced by 0.75% and 4.24%, respectively, and the jet length is reduced by 1.85%. Compared with scheme IV with a low detonation velocity single-layer charge structure, the jet head velocity and tail velocity of scheme I are increased by 18.45% and 9.3%, respectively, and the jet length is slightly reduced. The jet head velocity, jet tail velocity, and jet length of scheme V are better than those of scheme (I) scheme II and scheme IV. However, the jet formability of scheme III is better than that of scheme V when the explosive with higher detonation velocity is used in the outer charge of a double-layer shaped charge, in which the jet length is increased by 2.18%. The velocity of the jet head is increased by 1.40%, which is beneficial to improve the penetration depth.

The utilization ratio of the liner is the ratio of jet mass to liner mass. A good utilization ratio of the liner is beneficial to the formation of the stable metal jet. The utilization rate of the liner of single-layer and double-layer charges is obtained, as shown in Figure 8 (30 μs), where η is the utilization rate of the liner. The inner high and outer low type double-layer shaped charge has a higher utilization ratio of the liner, and the utilization ratio of the liner with single-layer structure is significantly higher than that of the inner low and outer high type double-layer shaped charge. For a single-layer structure, the utilization ratio of the liner increases slowly with the increase of detonation velocity. For the inner low and outer high type double-layer shaped charge, the utilization ratio of the liner increases slowly with the increase of detonation velocity. When the detonation velocity difference between the inner and outer charge increases, the utilization rate of the liner increases slightly.

5. Influence of Structural Parameters of Sandwich Charge on Jet Forming

5.1. Influence of Cone Angle of Liner. TNT and B explosives are selected for the inner and outer charges, respectively. α is the cone angle. The cone angles of the liner in schemes A, B, C, and D are 55°, 60°, 65°, and 70°, respectively. The variation of θ of different cone angles is shown in Figure 9, where L is the axial distance between the Mach impact point and the initiation center, θ increases rapidly at first and then slowly with the increase of L. Scheme A has the least regulating effect on the detonation wave and forms a convergent

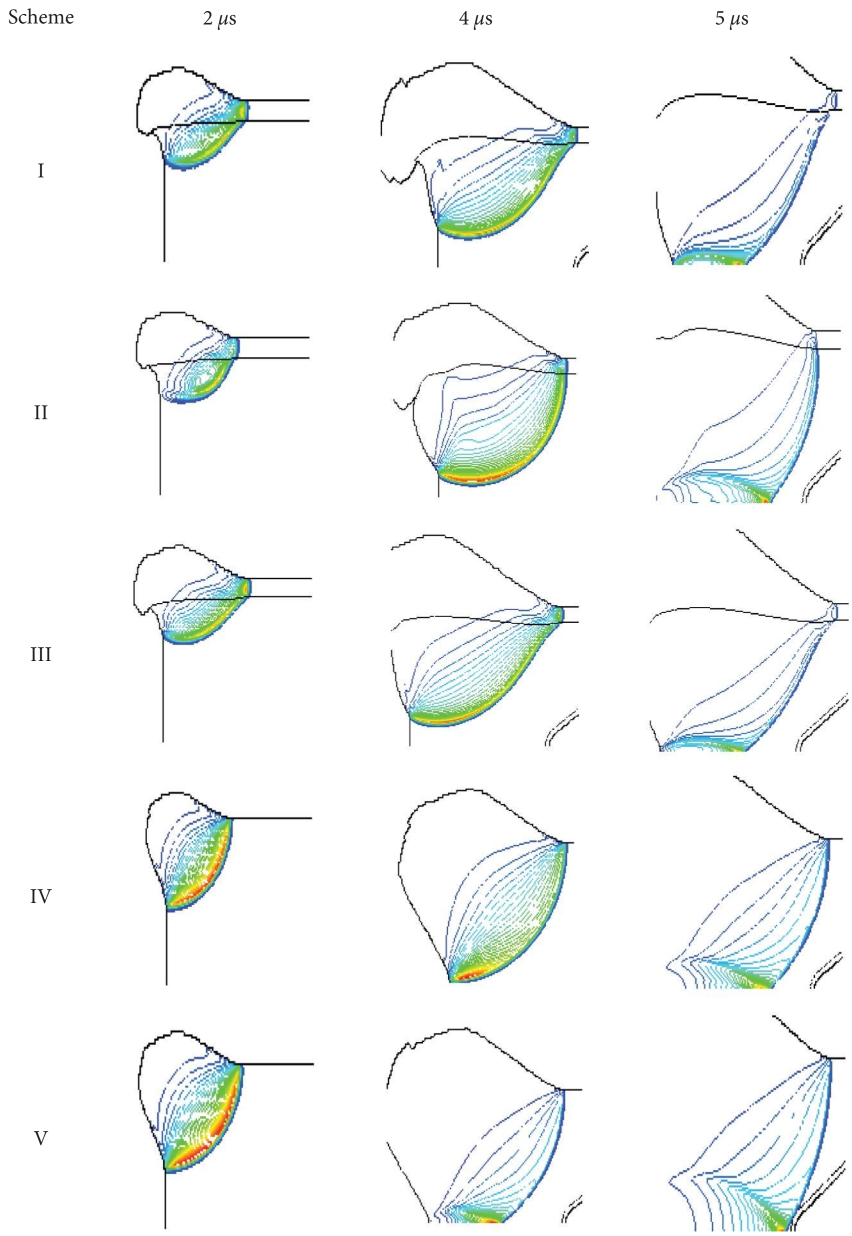

Figure 5: Detonation wave shape of single-layer charge and double-layer charge.

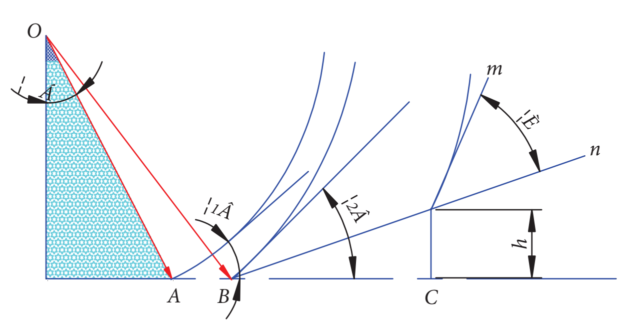

Figure 6: Detonation wave propagation process.

detonation wave first. Schemes B, C, and D have a less regulating effect on detonation waves, and the ability to produce convergent detonation wave increases gradually.

Figures 10 and 11 show the jet velocity gradient and liner utilization under different cone angles. X is the axial distance from the initiation center. It can be seen from the

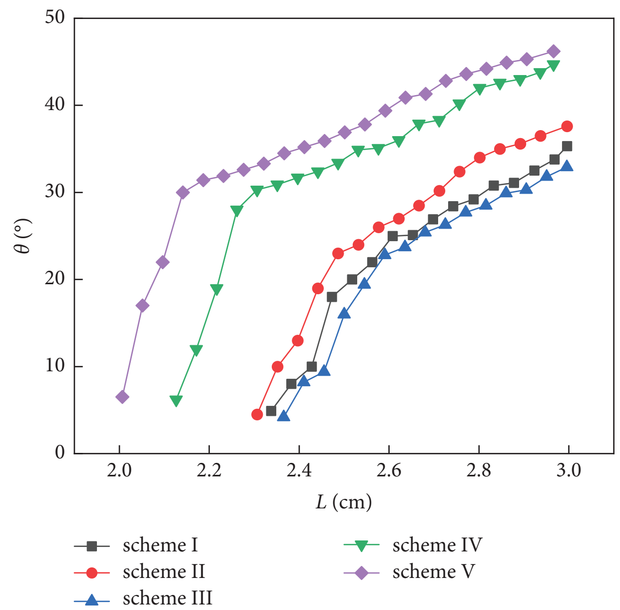

Figure 7: Variation rule of θ of single-layer charge and double-layer charge.

Table 2: Jet formation parameters of single-layer charge and double-layer charge.

Scheme	V_T (km/s)	V_W (km/s)	L (mm)
I	8.0390	2.0269	131.04
II	7.9790	1.9410	128.61
III	8.233	2.0271	135.27
IV	6.7870	1.8544	132.31
V	8.1194	2.1954	132.40

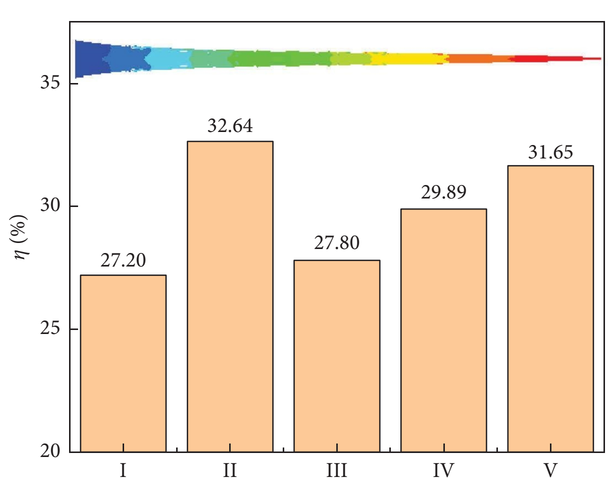

Figure 8: The utilization rate of single- and double-layer charges.

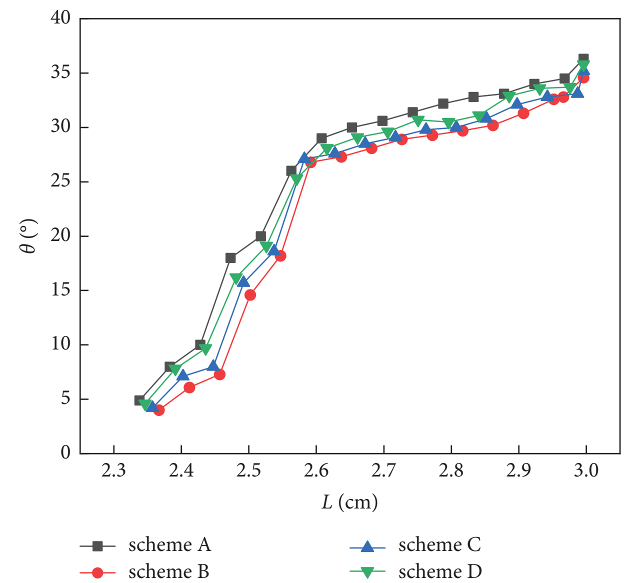

Figure 9: The variation of θ of different cone angles.

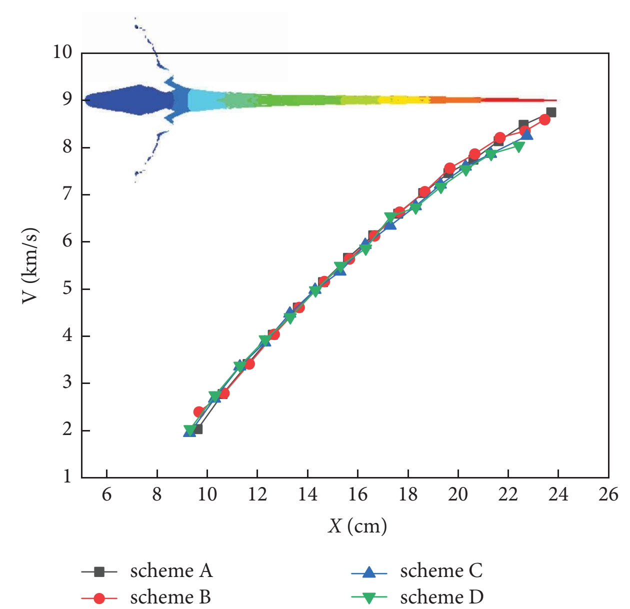

Figure 10: The velocity gradient of a jet of different cone angles.

velocity gradient curve in Figure 10 that the variation trend of jet velocity under four kinds of liner cone angles is relatively uniform, and the velocity and jet length are better than those of the other three schemes when the liner cone angle is 55°. When the cone angle of the liner increases to 70°, the utilization rate of the liner increases slowly. This is mainly due to the fact that the detonation wave incidence angle increases with the increase of the cone angle when the charge is driven by the double-layer charge detonation wave.

5.2. Influence of Charge Height. TNT and B explosives are selected for the inner and outer charges, respectively. The charge heights of schemes E, F, G, and H are 7.33 cm, 9.33 cm, 11.33 cm, and 13.33 cm, respectively. Figure 12 shows the jet velocity gradient curve. With the increase of charge height, the length of the jet is smaller.

Figures 13 and 14 are the curves of Mach rod pressure and density, respectively. L is the axial distance between the Mach rod and the initiation center. The higher the charge

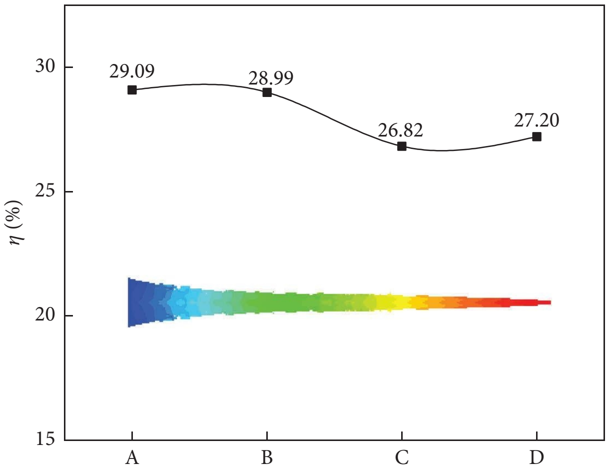

Figure 11: The utilization rate of the liner of different cone angles.

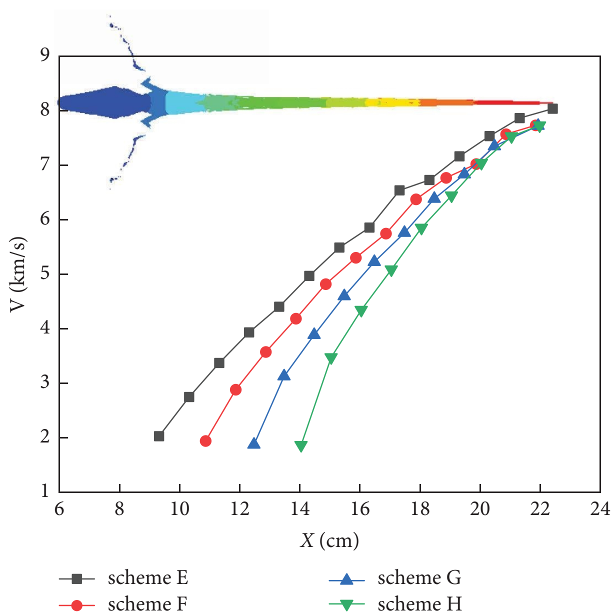

Figure 12: Jet velocity gradient at different charge heights.

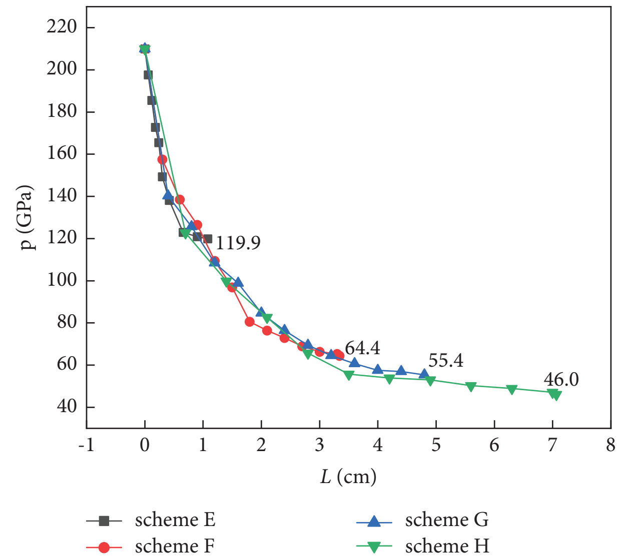

Figure 13: Mach bar pressure variation at different charge heights.

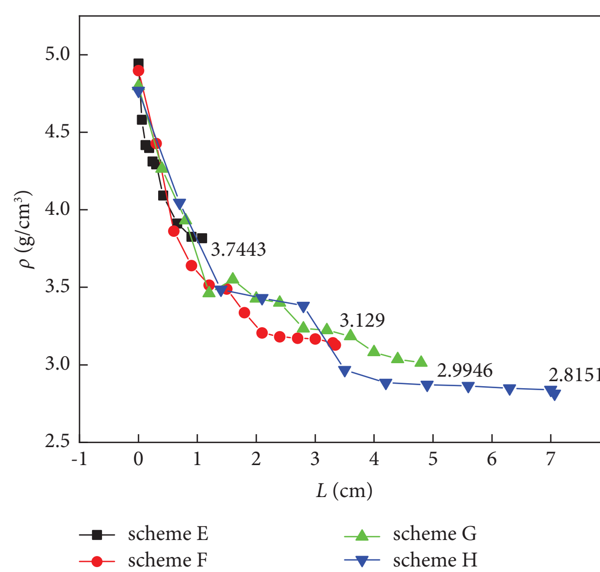

Figure 14: Density variation of Mach reflection overpressure region with different charge heights.

height is, the easier it is to produce a convergent detonation wave. It can be seen from Figure 13 that the detonation pressure of the four schemes can reach 210 GPa at the beginning of Mach collision, which is 10 times the C-J pressure. With the progress of detonation, the Mach rod height changes continuously, and the pressure gradually decreases. When the liner is crushed, the detonation pressure gradually decreases to 5.7 times the C-J pressure 3.1 times, 2.6 times, and 2.2 times. It can be seen from Figure 14 that the density of the Mach rod gradually decreases at first and then tends to be stable, and the stable density is 2.3 times, 1.9 times, 1.8 times, and 1.7 times the inner charge density, respectively.

With the increase of the charge height of the double-layer shaped charge, the energy of the final charge keeps increasing, but the jet head velocity and jet tail velocity do not increase accordingly. On the one hand, it is affected by the effective charge height; on the other hand, with the increase of the charge height, the pressure and density of the Mach rod gradually decrease when the pressure and density of the liner collapse. When it decreases to the C-J pressure and density, its detonation will also be transformed from overpressure detonation to ordinary detonation. The length of the jet decreases gradually, but the utilization rate of the liner keeps increasing, indicating that with the increase of the charge height, the stability of the metal jet is improved, which is mainly manifested by the more obvious role of reaming.

5.3. Influence of Radius Ratio of Inner and Outer Charge. TNT and B explosives are selected for the inner and outer charges, respectively, and the radius ratios of the inner and outer charges of schemes I, J, K, and L are 0.79, 0.83, 0.89, and 0.94, respectively. Figure 15 shows the detonation wave waveform of a double-layer shaped charge with inner and outer charge radius ratios of 0.79, 0.84, 0.89, and 0.94, respectively. With the increase of the radius ratio of the inner and outer layers, the angle between the detonation wavefront and the axis of the charge decreases gradually, that is to say, the regulation effect of the outer layer charge on the detonation waveform becomes more and more obvious.

Figure 16 shows η and L of different charging radius ratios of the inner and outer layers. When the ratio of inner and outer charge radius increases, the efficiency of the liner decreases slowly. The lower the radius ratio of inner and outer charges, the easier the convergent detonation wave will be produced.

In order to analyze the change rule of jet velocity, the jet velocity at 30 μs was intercepted, as shown in Figure 17. X represents the axial distance between the jet flow and the initiation center. As can be seen from the change curve of the jet velocity gradient in Figure 17, the jet velocity gradient of the above four schemes is uniform, and the jet length is slightly different. If the analysis is made only from the intercepted jet velocity gradient at 30 μs, the ratio of the inner and outer layer charge radius has little influence on the jet velocity gradient, but it has a certain influence on the jet velocity size and jet length.

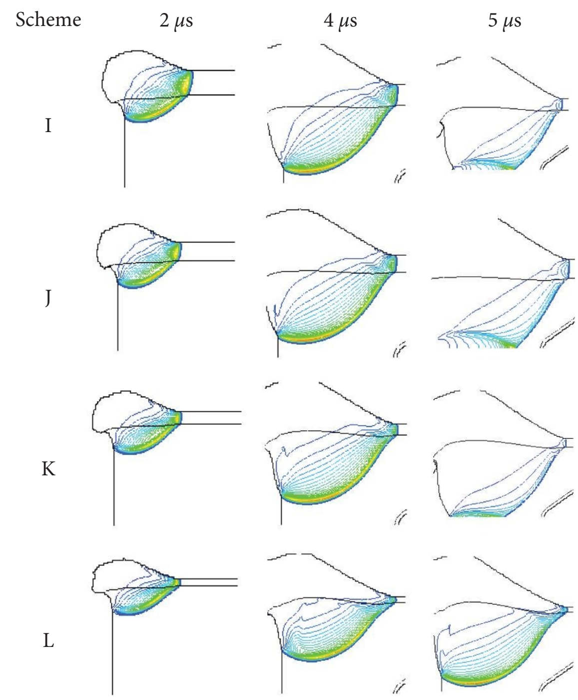

FIGURE 15: Detonation wave shape with a different charging radius ratio of inner and outer layers.

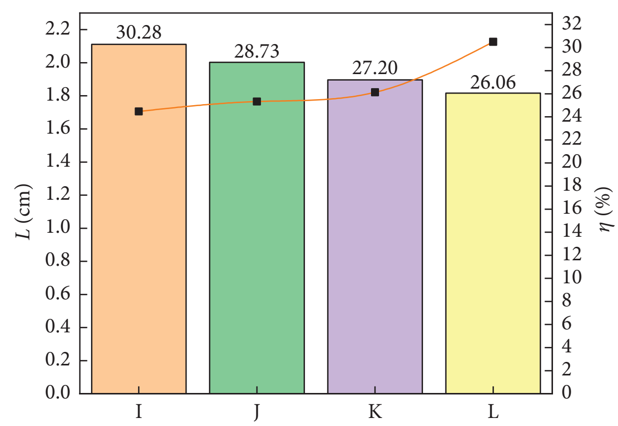

FIGURE 16: η and L of different charging radius ratios of inner and outer layers.

6. Results and Discussion

Based on AUTODYN numerical simulation software, the detonation wave propagation process and jet-forming parameters of single-layer charge and double-layer shaped charge structure under ring initiation are simulated and compared.

(1) For the double-layer shaped charge with low inside and high outside, the detonation wave of the outer charge always propagates ahead of that of the inner charge, which has a good regulating effect on the detonation wave shape. In the initial stage, the detonation wave propagation of the outer charge is prior to that of the inner charge. With the continuous propagation of the detonation wave, the propagation speed of the detonation wave of the inner charge begins to be faster than that of the outer charge. The outer charge has no obvious regulating effect on the detonation wave. The detonation wave of the single-layer charge is similar to that of the double-layer shaped charge with the high inner and low outer charge when the detonation wave of the inner charge overtakes that of the outer charge, but the increase of the angle between the detonation wave front and the axis of the charge is more obvious when the detonation velocity of the single-layer charge is higher.

(2) When the cone angle of the liner of the sandwich-shaped charge is 60°–70°, with the increase of the cone angle of the liner, the regulating effect of the outer charge on the detonation wave decreases gradually. When the charge height of the double-layer shaped charge increases gradually, the variation law of the detonation wave is similar to that of the sandwich-shaped charge, that is, the regulating effect of the outer charge on the detonation wave decreases gradually, which is conducive to the formation of the convergent detonation wave. On the contrary, when the ratio of the inner and outer charge radius of the sandwich-shaped charge is 0.79–0.94, the regulating effect of the outer charge on the detonation wave increases with the increase of the ratio of the inner and outer charge radius.

(3) With the increase of the cone angle of the liner, the jet head velocity and jet length decrease gradually. With the increase of charge height, the head velocity,

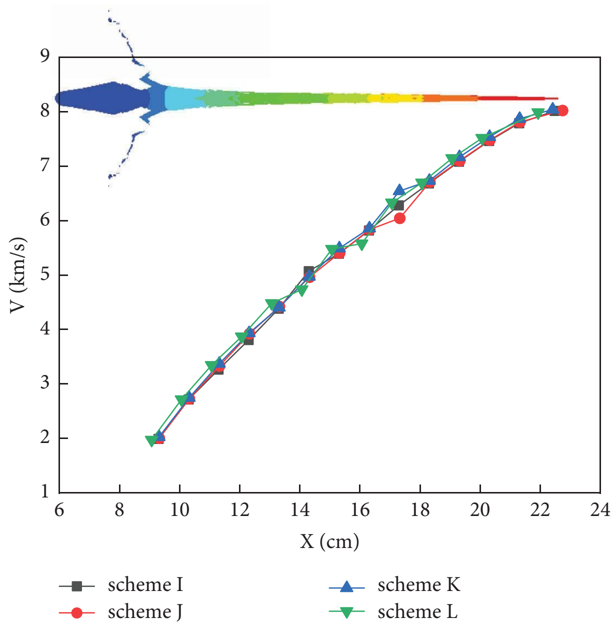

Figure 17: Jet velocity gradient with different charging radius ratios of inner and outer layers.

tail velocity, and jet length of the jet decrease, and the jet velocity gradient increases gradually. The pressure and density of the Mach reflection zone decrease slowly, but the liner utilization increases gradually. With the increase of the radius ratio of inner and outer charges, the jet head velocity and tail velocity first increase and then decrease, and the jet length and liner utilization increase; with the increase of the detonation velocity of the outer charge, the jet head velocity, the jet tail velocity, and the jet length increase in turn, but the jet density decreases gradually, which is not conducive to improving the penetration depth of the jet.

The results of this study are consistent with those of the literature [14]. In the literature, the jet head velocity of the double-layer explosive with high and low detonation velocity is 22% higher than that of the single structure, and the result obtained in this paper is 18.4%. The detonation waveform of the double-layer charge with high and low detonation velocity is horn shaped, which reduces the incidence angle of the detonation wave to the medium. Constant and stable Mach overpressure plays an obvious role in improving jet velocity.

7. Conclusion

In order to improve the penetration ability of shaped charges, the key is to improve the energy utilization rate of the double-layer shaped charge. In this paper, by comparing the detonation wave shape and jet-forming parameters of single-layer and double-layer shaped charges, it is found that the double-layer shaped charge with low-detonation velocity inside and high-detonation velocity outside has a good regulating effect on the detonation wave shape. The overpressure detonation waveform can keep a good match with the liner. With the increase of the cone angle of the charge and the charge height, the adjustment effect of the outer charge on the detonation wave gradually decreases, which is conducive to the formation of the convergence detonation wave. On the contrary, the adjustment effect of the outer charge on the detonation wave gradually increases with the increase of the charge radius ratio of the inner and outer layers. With the increase of the cone angle, the jet head velocity and length decrease gradually. With the increase of the charge height, the jet head velocity, tail velocity, and jet length all decrease, and the jet velocity gradient gradually increase. The pressure and density in the Mach reflection zone slowly decrease, but the utilization rate of the liner gradually increases. With the increase of the charge radius ratio of the inner and outer layers, the jet head velocity and tail velocity first gradually increase and then decrease, and the jet length and the utilization rate of the liner gradually increase.

Data Availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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References

[1] Z. Y. Liu, *Overdriven Detonation Phenomenon and its Application to Ultra-high Pressure Generation*, Kumamoto University, Kumamoto, Japan, 2001.
[2] L. V. Altshuler, V. N. Zubarev, and G. S. Telegin, “Supercompressed detonation waves in condensed explosives,” *Combustion, Explosion and Shock Waves*, vol. 10, no. 5, pp. 648–652, 1974.
[3] T. Hamada, “The performance of pressure vessel using concentric double cylinder high explosive,” *Journal of Pressure Vessel Technology*, vol. 126, no. 4, pp. 319–326, 2004.
[4] Z. Y. Liu, K. Shiro, and I. Shigeru, “Numerical study on hypervelocity acceleration of flyer plates by overdriven detonation of high explosive,” *International Journal of Impact Engineering*, vol. 26, no. 10, pp. 443–452, 2001.
[5] T. Hamada, S. Itoh, and H. Kato, “An investigation on overdriven detonation phenomenon in concentric double cylindrical high explosive,” *Materials Science Forum*, vol. 466, pp. 379–384, 2004.
[6] H. Kato, K. Murata, and S. Itoh, “Application of overdriven detonation in high density explosive to shaped charge,” in *Proceedings of the 23rd International Symposium on Ballistics*, pp. 223–229, Tarragona, Spain, July 2007.
[7] X. F. Zhang and L. Qiao, “Studies on jet formation and penetration for a double-layer shaped charge,” *Combustion, Explosion and Shock Waves*, vol. 47, no. 2, pp. 241–248, 2011.

[8] T. Hussain, Y. Liu, and F. L. Huang, "An analysis of double layer shaped charges," in *Proceedings of the 29th International Symposium on Ballistics*, pp. 1314–1321, Edinburgh, Scotland, June 2016.

[9] T. Hussain, Y. Liu, and F. Huang, "Overdriven detonation and its application in shaped charges," *Journal of Beijing Institute of Technology (Social Sciences Edition)*, vol. 26, no. 1, pp. 9–15, 2017.

[10] H. Wang, F. Shen, and Q. Z. Tian, "Wave scanning experiment of composite charge under eccentric initiation," *Chinese Journal of Energetic Materials*, vol. 23, no. 11, pp. 1041–1045, 2015.

[11] K. Ha, "Innovative blade trailing edge flap design concept using flexible torsion bar and worm drive," *HighTech and Innovation Journal*, vol. 1, no. 3, pp. 101–106, 2020.

[12] M. Fouad, M. N. Fayed, G. A. Hamdy, and A. Abdelrahman, "Effect of blast loading on seismically detailed RC columns and buildings," *Civil Engineering Journal*, vol. 7, no. 8, pp. 1406–1425, 2021.

[13] D. T. A. Ansori, A. R. Prabowo, T. Muttaqie et al., "Investigation of honeycomb sandwich panel structure using aluminum alloy (AL6XN) material under blast loading," *Civil Engineering Journal*, vol. 8, no. 5, pp. 1046–1068, 2022.

[14] X. F. Zhang, J. B. Ding, and X. N. Zhao, "Numerical simulation of double layer shaped," *Explosion and Shock Waves*, vol. 29, no. 6, pp. 617–624, 2009.