

Chapter 2

Explosion Features of Liquid Explosive Materials

As everyone knows that the explosion characteristics of explosive materials have close relationship with their packed density and structures. Liquid explosive materials are noncompressible. One of the notable characteristics is that its excellent detonation is not influenced by its phase, shape, and geophysical environment. Its application is much broader than the condensed explosive materials. When a liquid explosive material explodes in unlimited free spaces, though the super pressure is lower than that of condensed explosive materials, the shock pulse is broader and positive action lasts longer. Its performance is better. Especially in semiconfined spaces, a liquid explosive material releases gas materials and the nearby oxygen (gas) also takes part in the detonation reaction. This oxygen absorption reaction is an excellent characteristic, which is not indicated by general condensed explosive materials. Liquid explosive materials follow the explosion factors, and have their special detonation reactions, which are different from the general explosive materials. The detonation processes have close relationship with their low-pressure denotation. This chapter studies the detonation mechanism of liquid explosive materials, and discusses their explosion characters, lets detonation characteristics understood, and supplies technical support for the applications.

2.1 Explosion Phenomena and Key Factors of Liquid Explosive Materials

Explosion is a phenomenon of physical or chemical changes within extreme short time. In the changing processes, the energy inside the explosive materials changes from one form to another, such as from reactant to production, or from chemical energy to the compression energy or kinetic energy of their media. One of the key features is that huge amount of energy is released or transformed within certain space. The energy accumulation within extreme time and limited space leads to a high-temperature and high-pressure condition. This nontraditional environment with rapid pressure rise followed complex movement resulting in abnormal shift or mechanical damage. The most external/obvious feature of explosions is that the media give the audible effect after a shake. In general, explosion has two stages.

First, the energy with certain form transforms to the compressing energy of products. Then the compressed materials expand rapidly, while the compressing energy changes into mechanical energy, which leads to the shape change, damage, or shift of the around media. Physical change leads to physical explosion, while chemical change results in chemical explosion.

In our daily life, the most common physical explosion is lightning. It is a spark discharge. Within the discharge space, the energy density and temperature of the media raise to an unbelievable high condition (e.g., several ten kilo degrees Celsius) within extreme short time. This leads to the fast pressure increase of the discharged air and explosion. All explosions from high-pressure cookers, steam boiler, high-pressure compressed gas cylinders, and earthquakes are physical ones.

Explosions from liquefied gas pipes, gasoline tanks, chemical processes of industry, gas inside mines, coal dust, and all explosive materials are chemical explosions. The explosion caused by mixtures of inflammable liquid leakage and air is also chemical one. All stuffs, which can have chemical explosions, are named explosives. If the used staff is in liquid or sol-gel, this is the explosion from liquid explosive materials. This chapter studies the explosion variation law and features of liquid explosive materials.

The explosive abilities are determined by the exothermicity, rapidity, and gas production of explosion reaction.

2.1.1 Heat/Energy Releasing of Liquid Explosive Explosion

All explosion reactions are exothermic with the formation of new molecules. Considering the decomposition of a compound, certain amount of energy must be supplied to activate the molecules or break the chemical bonds, which subsequently generate new compound and release heat. If the released heat cannot activate the subsequent reactions, the chemical reactions will terminate automatically. To maintain such a reaction, energy has to be supplied from the environment. Obviously, these materials are not explosives. If the energy released from the initial explosive reaction activates the unreacted molecules, and the explosive reaction propagates continually until all reactants are consumed.

Explosion is a process in which energy transforms rapidly. Explosion produces stable compounds by transforming chemical energy into heat. The heat is then transformed into the mechanical work of media. Endothermic reactions or exothermic reactions with less heat released are not explosion. For example,

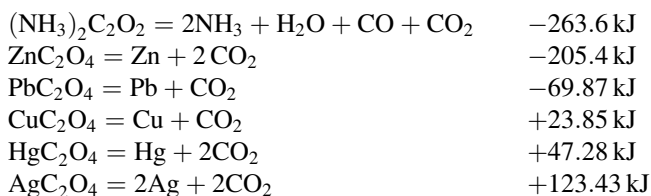


Table 2.1 Released energy comparisons of various fuels

Materials	Explosion heat (kJ/kg)	Mixtures with air (kJ/kg)	Mixtures with air (kJ/L)
Wood	18,828	7,950	19.7
Coal	33,472	9,205	17.99
Gasoline	41,840	9,623	17.6
Black powder	2,929	2,929	2,803
Nitrotoluene (TNT)	4,184	4,184	6,485
Nitroglycerine (NG)	6,276	6,276	10,042
Octogen (HMX)	5,530	5,530	10562.3
Hexanitrohexaazaisowurtzitane (CL-20)	6,028	6,028	12319.4

All above reactions are the decomposition of citrates and have similar products. In decomposition processes, their exothermicities are different. All citrates with endothermic decomposition reaction are not explosive materials. Only silver citrate and mercury citrates with exothermic decomposition reaction are explosive. Although copper citrate has exothermic decomposition reaction, the heat is too less compared to the general explosive materials. Copper citrate can cause explosion, but a weak explosion. However, the heat released in explosion from explosive materials is probably not much. If counted in unit weight, this heat is probably lower than fuels. Why explosive materials can have violent explosion? Because explosive materials release more energy in unit volume, and the energy density is very high. Table 2.1 shows the comparison of released energy by different materials.

Table 2.1 indicates that the energy/heat released by explosive materials per unit kilogram is much lower than that by fuels, just part of the energy/heat that fuels release in combustion. The density of air is very low compared to fuels and explosive materials. But the energy/heat of explosive materials is about 130–600 times that of fuels. The energy of explosive materials is concentrated, and energy density is higher.

2.1.2 Rapid Reaction of Liquid Explosive Materials

The second necessary condition of explosions is the rapidity of reactions, which differentiates the general chemical reactions and explosions. Explosive materials per unit weight have less energy than fuels. However, the combustion of general fuels per unit weight has more energy/heat than explosive materials. These combustion reactions plod slowly. The energy aggregation and release conduct in a rapid speed. Rapidity of energy release is one of the most obvious features of explosion. Per kilogram coal releases 25,940 kJ after complete combustion. While per kilogram nitroglycerine only has 6213.2 kJ. The energy from per kilogram coal is about 4.175 times than that of nitroglycerine. The complete combustion of 1-kg coal needs

several to more than 10 min. However, the explosion of nitroglycerine finishes within 1/100–1/1000000 s. Explosion reaction is about 100–1,000 times faster than the combustion of general fuels. Both explosion and combustion reactions release a lot of heat and large volume of stable gas finally. Combustion reacts slowly. There is enough time for gas transportation, and no high-pressure space forms. While the rapidity of explosion limits the expansion of gas products, the energy is confined to the original volume of explosive materials, and the energy density is extremely high. The as-prepared high-temperature and high-pressure gas products let explosion powerful and damaging. For example, the energy released by one-kilogram explosive materials equals the electricity that a 1,000 W motor needs to work for an hour.

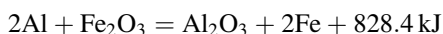


This reaction is familiar for most of us. The combustion of coal in air releases large amount of heat and gas production. But coal combustion is not explosion. Only when oxygen diffuses onto the surface of coal, combustion reacts. This process is very slow. And the produced energy and gas diffuse into the atmosphere gradually. The space of energy is open. Neither high temperature nor high pressure is created. There is no mechanical interaction with the environment. If coal powders with ~ 200 nm diameters are obtained by grinding, and suspended in the air, violent explosion takes place after a flash. Explosive power increases following that the diameters of powders become smaller. The main reason is that the dramatic increase in surface area per unit weight and complete contact of surface with oxygen results in rapid combustion reaction.

2.1.3 Gas Products in Explosion of Liquid Explosives

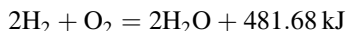
Explosions of liquid explosives affect the nearby media using the speedy expansion of high-temperature and high-pressure gases. Immediate release of large amount of gas is one of the key features in explosion reactions. Explosion of nitromethane (1 L, 1,140 g) produces $\sim 1,464$ L (std) gas and explosion of isopropyl nitrate (1 L, 1,040 g) generates $\sim 1,551$ L gases. While in explosion, TNT (1 L, 1,600 g) begets 1,656 L gas production. Because of exothermic and rapid reactions of explosions, huge amount of gas production limited in the original little space is heated to extreme high temperature. High-temperature and high-pressure gases violently affect the environment in mechanical work.

There are other materials, whose reactions are rapid and release a lot of energy/heat at the same time. However, the reactions do not generate gas productions. These materials are not explosives. Take thermite reaction as an example,



The heat released in this reaction is enough to raise the temperature of products at 3,000 °C while Fe and Al_2O_3 are liquids now. No gas is produced in this reaction, and it is nonexplosive.

In certain conditions, rapid and exothermic reactions without gas production also lead to explosion. E.g., reactions of well-grounded thermite reactants in the air make the nearby air heated and expand, and then explode. This explosion comes from the heated air, not the reaction of thermites. Sometimes the amount of gases reduces rather than increase, especially the explosive reaction of gas reactants. The explosion of detonation gas is listed below.



In above reaction, 1/3 amount of gases is cut off. The rapidity and exothermicity make up the reduction of gas amount. The volume of gases increases rapidly under high temperature. If the volume is maintained, the pressure reaches more than 10 atm within an extreme short time. This is the key feature of detonation gases.

In summary, exothermicity, rapidity, and gas productions are key features of explosive reactions. Exothermicity of reactions supplies the initiating energy for explosion. Rapidity is the must condition which helps to confine the limited energy into small space, while produced gases are media of energy conversion. Explosion power has close relationship with exothermicity, rapidity, and gas productions. Exothermicity helps heat explosive to a relative high temperature, which increases the reaction speed and makes the reaction reach rapidity. In addition, the released energy dramatically increases the temperature and promotes the conversion of reaction products into gas state.

The chemical structures and physical states of explosive determine whether they explode or not. But, to some degree, different explosives are different in amount of released energy, reaction speeds, and gas productions. In general, explosion reactions must have the three key features: exothermicity, rapidity, and gas productions. This is applied for all explosions.

2.2 The Explosion Changing of Liquid Explosive Materials

Liquid explosives are noncompressible, and are different from condensed explosives. In the explosion, liquid explosives should be gasified first, later ignited. Once this abnormal combustion reaction becomes normal one, self-sustaining spread detonation follows. The explosion changes of liquid explosives have two classic forms: combustion and detonation.

2.2.1 Combustion of Liquid Explosives

Combustion reaction of explosives is deflagration, which is another classic form. Deflagration is different from general combustion. Explosives have oxidants and combustible materials. Combustion of explosives does not need the oxygen in air, and it spreads smoothly. For propellants and pyrotechnics, combustion is the basic form of explosion. Some primary explosives work through combustion or combustion–detonation. Here in all, study of the general rules of liquid explosives and the basic conditions of combustion-to-detonation are of great importance for the safety productions and applications of liquid explosives.

2.2.1.1 General Features of Combustion of Liquid Explosives

Combustion is very common, e.g., combustion of wood, coal, etc. The chemical reactions with light and heat released are combustion. The space with light and high temperature of chemical reaction is named as flame. The geometric surface of separating burning layer from nonreaction zone is the flame front.

The combustion of liquid explosives leads to violent chemical reactions, which spread themselves. It is different from the combustion of general fuels. The combustion of liquid explosives can be isolated from air, and the oxidations depend on the oxygen of the explosive. This combustion is also deflagration. The processes of explosive combustion are the processes in which flame fronts spread themselves [1]. Spreading of flames is determined mainly by conduction of heat and diffusion of combustion productions [2].

Combustion of liquid explosives is different from that of condensed ones. Liquid explosives are noncompressible, and have fixed density, and their combustion spreading is continuous and fast. There are two stages for the combustion process of liquid explosives. First, the surfaces of liquid explosives flame. Then, the flame spreads into the inside of the liquid explosives. The burning reaction spreads along the interface of liquid explosives and air is surface combustion, while the burning reaction spreads along the normal directions is section combustion. Starting of liquid explosive combustion has two ways: spontaneous ignition and forced ignition. Spontaneous ignition is produced through the self-acceleration of chemical reactions of liquids. Forced ignition is reached by external heat source at high temperature. Forced ignition is common in the application of liquid explosives. To ignite the liquid explosives, fire source should have enough high temperature and enough heat to supply.

Burning speed is an important parameter of combustion. There are two ways to show the burning speed: linear speed of flame front spreading and mass speed of combusted liquids. The linear speed (u) of flame front spreading along the liquid

explosives is the reacted volume within unit time and unit area of flame fronts (Eq. 2.1).

$$u = \frac{V}{S} \quad (2.1)$$

Here, V represents the burned/combusted volume within unit time; S represents the total surface area of flame fronts.

The mass speed (m) of combustion is defined as the mass amount of explosives consumed per unit time and unit flame front area. The mass speed of combustion is a function of the explosive density and the linear speed (Eq. 2.2).

$$m = \rho u \quad (2.2)$$

Combustion process has stable and unsteady combustions. The stable combustion of explosives presents that single component explosive has a constant burning/combustion speed under certain conditions (e.g., fixed pressure, temperature, packed density, etc.). Most of liquid explosives can reach stable combustion. The combustion of explosive is not always stable. For mixed liquid explosives, the combustion speed may accelerate or slow down, sometimes accelerate or slow down suddenly. The main reason is the nonuniformity of mixtures.

Acceleration of unsteady combustion leads to faster combustion, finally detonation. Slowing down results in the slower combustion, to burning off. Whether an explosive explodes finally is determined by its combustion speed.

2.2.1.2 Combustion of Volatile Liquid Explosives

Liquid explosives have different volatilities, which varied the combustion processes. The important characteristic is the variation of reaction phase in the combustion reactions. Generally, because alkyl nitrates and some of alkene nitrates are highly volatile, their combustion reactions proceed in gas state. In contrast, the combustion reactions of nitroglycerine, azide nitrate ether, and aqueous hydrazine proceed in both gas and solid phases. The reactions of mercury fulminate and urea perchlorate mainly proceed in solid state.

To simplify the flame propagation, the assumption is based on flame propagation with a fixed speed toward the liquid in only one dimension. Butyl nitrate is filled in a pipe. The ignition device is used to induce the combustion of liquid explosives from one end. At first, only the explosive (which is very close to the ignition device) starts burning. The propagation of flames is shown in Fig. 2.1.

The propagation of flames proceeds the reaction zone forward till the end of the pipe. The flame fronts isolate the reacted and nonreacted zones. Every moment of flame propagation reaction is in process of the thin layer close to flame fronts. The preheating layer isolates the nonreact zone and flame fronts. The speeds of flame propagation are determined by the chemical properties of liquid explosives.

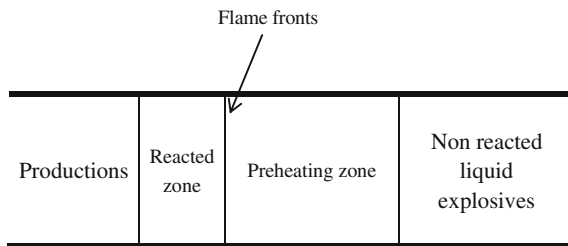


Fig. 2.1 Schemes of flame spreading of volatile liquid explosives

In ignition or combustion, the energy transferred to the surface of explosive is to activate reactions and evaporate the molecules. If the evaporation is faster than reactions, the combustion is conducted under gas phase after liquids become gases.

In the combustion, the surface layer receives heat Q and its surface temperature raises to T . The reaction proceeds under $MAe^{-E/RT}$ speed (M is the mass of pre-heating zone) for one molecule mechanism, while the evaporation undergoes $M'v e^{hv/RT}$ (M' is the mass of evaporative materials/molecules. v is the vibration frequency, and hv is heat of evaporation per mole).

Now let's compare all the parameters in the equation by starting with M and M' . When the vapor pressure of liquid explosives is higher than the outside pressure, all liquid explosives evaporate. When the vapor pressure of liquid explosives is lower than the outside pressure at temperature T , the evaporation only occurs on the liquid surface, and not the whole heating layer will evaporate. Under this condition, $M' < M$.

During the combustion of explosives, the heat is only transferred onto the surface. Because of the surface evaporation, the energy cannot reach the deep inside of explosives. Under this condition, M' is approximately equal to M . In the first order reaction, A is similar to v , the vibration frequency of molecules per minute, which is about 10^{13} – 10^{14} .

To further explain the reaction in the liquids, $e^{-E/RT}$ is compared with $e^{-hv/RT}$. $e^{-E/RT}$ represents the possibility of obtaining activation energy E for each molecule. $e^{-hv/RT}$ is the possibility of receiving evaporation energy hv of one molecule.

Alkyl nitrates and part of alkene nitrates are volatile materials when the temperature is close to the breaking point. Their evaporation energy hv is much smaller than activation energy E .

For most volatile liquids, their evaporation energy is less than 41,800–50,200 J/mol, while their activation energy is more than 12,500–15,600 J/mol. At 200 °C, diethyleneglycol dinitrate has activation energy $E = 146,440$ J/mol, while evaporation energy $hv = 41,840$ J/mol.

$$e^{-E/RT} = e^{-146440/1.99 \times 473.2} = e^{-155.51} \quad (2.3)$$

$$e^{-hv/RT} = e^{-41840/1.99 \times 473.2} = e^{-44.43} \quad (2.4)$$

At 200 °C, for each diethyleneglycol dinitrate molecule, the possibility of obtaining evaporation energy is 1,012 times of activation energy. The evaporation $M'v e^{-hv/RT}$ is much faster than the reaction $MAe^{-E/RT}$, even when M is larger than M' . For some explosives, A is larger than v . For nitroglycerine, $A = 1,020$ and E is also a large number ($E = 179,912$ J/mol). The speeds of evaporation and activation still follow the above conditions. It is concluded that the transferred heat evaporates the liquid molecules. The evaporation is much faster than reaction in the liquids. Evaporation processes absorb both the transferred energy and the released energy from reactions. The schematics of evaporation–combustion are shown in Fig. 2.2.

The temperature at the intersurface of the gas-condensed phase (N–N) is the boiling point, at which the vapor pressure of liquid explosives equals the environment pressure. The temperature of the condensed phase decreases with the increase of the distance to the intersurface, and it gradually reaches the starting temperature T_0 . Under this condition, there is a heating layer between gas and condensed phases. When no evaporation occurs, the heating layer becomes thicker with time prolong. In fact, because evaporation continues, the surface of condensed phase shifts and the shift of stable combustion is much faster than the heat conduction heating condensed phase. As a result, the thickness of heating layer does not change. According to some nonsystematic data, the heating layer of condensed phase is several millimeters at most when the amount of explosive is not large and it combusts. Because of the continuous evaporation of liquids, the preheating depth ($T_k - T_0$ step) does not change. The vapor formed by evaporation of liquids does not combust immediately; it needs time to be heated and for the reaction to progress. The combustion of vapor does not occur on the surface of the liquid, but at a certain distance from the liquid. Combustion proceeds in the preheating zone. The highest temperature of products is

$$T_1 = T_0 + \frac{Q}{C} \quad (2.5)$$

Here, T_0 is the original temperature; Q is the energy released from the combustion; and C is the heat capacity of products.

Later, the products are cooled down, and the temperature drops.

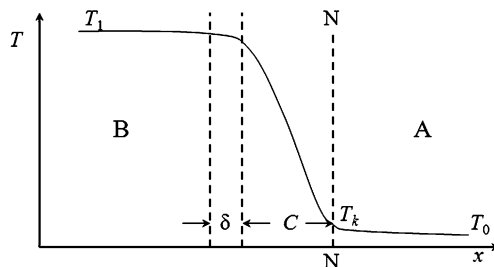


Fig. 2.2 Schematics of evaporation–combustion of liquid explosives A condensed phase; B production of combustion; T_0 , T_k , T_1 —temperature distribution curve

In the deduction of the explosive combustion, study of liquid and solid explosives separately is not a must. When heat is transferred to the solids, they start to liquefy. And the liquids follow the above combustion rules. Figure 2.2 indicates that the combustion of condensed explosives is similar to that of flammable gases under steady condition. The only difference is that for gas combustion all mixtures are gases while the gases are obtained by evaporation of liquids.

From the above analysis of volatile explosives, it is concluded that the mass speed of combustion equals the evaporation speed of liquids (Eq. 2.6).

$$\rho u = \rho_1 u_n \quad (2.6)$$

Here, u is the linear speed of evaporation; ρ is the density of explosives; u_n is the normal speed of evaporation–combustion; ρ_1 is the density of evaporation.

According to the equation of evaporation–combustion, the mass combustion speed of evaporation is Eq. 2.7.

$$\rho u = \sqrt{\frac{2\lambda}{q} \left(\frac{RT_1}{E} \right)^{n+1} (T_1 - T_0)^{-n} (n+1)! W(T_1)} \quad (2.7)$$

Here, T_1 is the temperature of combustion; $W(T_1)$ is the reaction speed at T_1 ; q is the heat of combustion; λ is the thermal conductivity of evaporations; n is the reaction order.

If the combustion is the first-order reaction, the mass combustion speed of volatile explosives is written in Eq. 2.8.

$$\rho u = 2 \frac{RT^2}{E} \sqrt{\frac{\lambda}{q(T_1 - T_0)}} \rho_2 A e^{-E/RT} \quad (2.8)$$

Here, ρ_2 is the evaporation density at T_1 ; A is the preexponential factor. The second equation of mass combustion speed is Eq. 2.9.

$$\rho u = \sqrt{\frac{2\lambda}{q} \left(\frac{RT_1^2}{E} \right)^{n+1} (T_1 - T_0)^{-n} (n+1)! D P^n e^{-E/RT}} \quad (2.9)$$

Here, $D P^n e^{-E/RT}$ is the reaction speed of several orders; n is the reaction order; D is the scale factor.

Equation 2.9 can be rewritten in Eq. 2.10.

$$\rho u = \sqrt{\frac{2\lambda}{q} \left(\frac{RT_1}{E} \right)^{n+1} (T_1 - T_0)^{-n} (n+1)! D e^{-E/RT} \sqrt{P^n}} \quad (2.10)$$

Because the value of the above square root has nothing to do with pressure, use B to replace it.

$$\rho u = B\sqrt{P^n} = BP^{n/2} \quad (2.11)$$

The linear speed of combustion is a function of pressure (Eq. 2.12).

$$u = \frac{B}{\rho} \sqrt{P^n} = bP^{n/2} \quad (2.12)$$

When the reaction is first order, the linear combustion speed of explosives is written in Eq. 2.13.

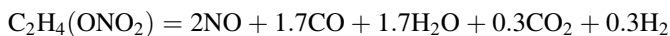
$$u = BP^{0.5} \quad (2.13)$$

When the reaction is second order, the linear combustion speed of explosives is written in Eq. 2.14.

$$u = BP \quad (2.14)$$

If the above index is 0.5–1, the assumed theory is correct.

To verify the correctness of above theory, experimental data of diethyleneglycol dinitrate are compared with theory ones. The combustion reaction of diethyleneglycol dinitrate in nitrogen (1 atm) is below.



The calculated combustion heat of diethyleneglycol dinitrate is 1921.05 J/mol, and the average heat capacity of products is 1.423 J/mol. In the combustion of diethyleneglycol dinitrate, the temperature increases $\Delta T = T_1 - T_0 = 1,350$ K. The detonation temperature is $T_1 = T_0 + \Delta T = 300 + 1350 = 1,650$ K.

At combustion temperature, the thermal conductivity of reaction products is $\lambda = 8.37 \times 10^{-4}$ J/cm s °C. The combustion reaction is a decomposition process, which is the first-order reaction. According to the chemical kinetics, the reaction speed is Eq. 2.15.

$$W(T_1) = \frac{M}{N} Z e^{-E/RT_1} \quad (2.15)$$

Here, M is the molecule weight of diethyleneglycol dinitrate; Z is the number of collisions; and N is Avogadro constant.

Combine Eqs. 2.15 and 2.7 at $T_1 - T_0 = \frac{Q}{C_p}$, the resulting equation is in 2.16.

$$\rho u = \sqrt{\frac{4\lambda R_2 T_1^4 \bar{C}_p M}{q^2 E^2} \frac{M}{N} Z e^{-E/RT}} \quad (2.16)$$

The collision number $Z = \sqrt{2}\pi d^2 u m^2$. Here, d is the diameter of diethyleneglycol dinitrate molecules; u is the molecular speed; m is the number of diethyleneglycol dinitrate molecules in cm^3 . According to kinetic molecular theory,

$$Z = \sqrt{6}\pi d \sqrt{\frac{RT_1}{M} \frac{P^2 N^2}{R^2 T_1^2}} \quad (2.17)$$

It is difficult to determine the diameter of diethyleneglycol dinitrate from experiments. Zeng et al. [3] analyzed the thermal decomposition mechanism of nitrate ether and suggested the diameter ($d = 5.10 \times 10^{-8} \text{ cm}$) of one ether, whose molecular weight is very close to diethyleneglycol dinitrate. The collision number is,

$$Z = 1.19 \times 10^{28}$$

Use the collision number in Eq. 2.16. Then, the calculated mass combustion speed is

$$\begin{aligned} \rho\mu &= \sqrt{\frac{4 \times 2 \times 10^{-4} \times 2^2 (1650)^4 \times 0.35}{(1921.05)^2 \times E^2} \times \frac{152}{6.10^{25}} \times 1.19 \times 10^{28} \times e^{-E/2 \times 1050}} \\ &= \sqrt{\frac{1.12 \times 10^{11}}{E^2} e^{-E/2 \times 1050}} \text{ g/cm}^2 \text{ s} \end{aligned}$$

The experiment data is $0.045 \text{ g/cm}^2 \text{ s}$. The activation energy of diethyleneglycol dinitrate is $146,440 \text{ J}$. These data match the calculated ones.

2.2.1.3 Combustion of Nonvolatile Liquid Explosives

When the nonvolatile liquid explosives are heated, they do not evaporate, but decompose before the temperature reaches the boiling point. The reaction in the liquid takes a very important part such as in nitro compounds, nitra-amine explosives, nitrocellulose gunpowders, nitroglycerine gunpowders, etc.

The combustion/reactions of the nonvolatile liquid explosives have three different stages.

The first stage is the exothermic reactions of the condensed phase. The reactions proceed on the surface or close to the surface. Because the reactions are in progress in the condensed phase, pressure does not impact a lot for the react rates, but temperature does. This reaction space is the condensed zone.

The second stage is the reactions of products from the first stage, and the reaction space is the gas phase intermediate reaction zone. The released heat from second stage is transferred to the condensed phase, and accelerate the reactions in the condensed phase.

The third stage occurs in the place, which is certain distance from the surface of condensed phase. The products from the second stage react violently. The reactions release a lot of heat, flames are generated, and final combustion products are engendered. Passing through intermediate reaction zone, the released heat is transferred to the condensed phase.

In the second stage, the temperature is relatively low, and the color of the intermediate reaction zone is dark blue. It is also named as flameless reaction zone.

In stable/steady combustion, the combustion speed of liquid explosives has a relationship of Eq. 2.18 with pressure.

$$u = a + bP^v \quad (2.18)$$

Here, u is the linear speed of combustion reactions; a is a constant which is determined by the reactions in condensed phase and the thermal conductivity; b is a coefficient which is determined by reactions in gas phase; v is an index which is determined by the reaction order of dominant reactions in gas phase.

Overall, for nonvolatile liquid explosives, proportion of reactions in condensed phase is the dominant at low pressure; the reactions of flame zone is the main stage at high pressure; while both reactions in condensed phase and flame zone works comprehensively.

2.2.1.4 Combustion of Fast-Burning Liquid Explosives

The combustion/burning speeds/rates of explosives are related to their evaporation. When the explosives are difficult to vaporize, the reactions in condensed phase take a large proportion. H_2O_2 -azidoethane is a traditional/classic explosive which is difficult to vaporize. In the combustion of H_2O_2 -azidoethane, the reactions in condensed phase are faster. They released a lot of gas products and heat burst the surface of condense phase violently. Then the gas products and some reactants go into gas phase directly and the reactions continue. The reactions terminate in the zone which is a little far from the intersurfaces. Under certain pressure and temperature, this preheating zone is fixed. The surface bursting of the condensed phase occurring with the vaporization together increases intersurface area and accelerates

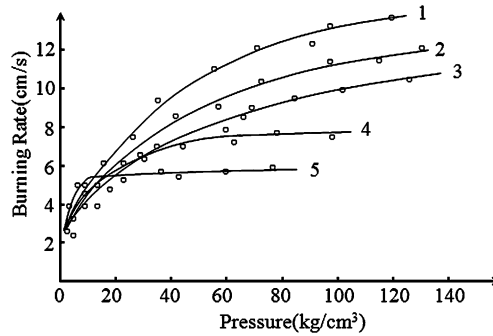


Fig. 2.3 The relation plots of combustion speed of H_2O_2 -azidoethane mixture and the pressure. 1 H_2O_2 -azidoethane; 2 N_2O_4 -unsym-dimethylhydrazine; 3 Mercury fulminate; 4 Nitroglycerine; 5 hexogen

the reaction. The combustion of this explosive is much faster than the above two kinds of explosives. The burning rate is a function of pressure.

$$u = a + bP^\nu$$

The index ν is about 0.5. Figure 2.3 indicates the relation between combustion speed of H_2O_2 -azidoethane mixture and the pressure.

The burning rate is less affected by pressure if the pressure is 20–40 atm. Probably, the reason is that the main stage of burning reacts in the condensed phase and the burning rate is controlled by the reaction in the condensed phase. This kind of explosive usually have large burning rates and high melting points.

2.2.1.5 Burning Stability of Liquid Explosives

The vortex of the liquids brings a disturbance for the flame front and results the deformation of flame front. So the burning stability of liquid explosives is broken. The deformation and disturbance increase gradually, and makes the burning rate lower, finally leads to the detonation. Stable burning reaches only when the mass burning rate is within certain ranges.

The gravity, surface tension, and viscosity of the liquids help to hinder the deformation of flame fronts. After calculating the stability impaction of gravity and surface tension, the normal burning limit rate is guaranteed if the below condition is met.

$$u_m = (4\alpha_k g \rho_1 \delta_1)^{1/4} \quad (2.19)$$

Here, u_m is the mass burning rate with unit $\text{g/cm}^2 \text{ s}$; α_k is the surface tension of a liquid and its saturated vapor; ρ_1 is the density (g/cm^3) of gas productions; δ_1 is the density of a liquid explosive.

According to α_k , ρ_1 , and δ_1 values from experiments, the calculated mass burning rates u_m of methyl nitrite, diethyleneglycol dinitrate, and nitroglycerine in one standard atmosphere press are 0.25, 0.26, and 0.25 $\text{g/cm}^2 \text{ s}$, separately. It is concluded that the right side of Eq. 2.19 is approximated as a constant. If the pressure is 1 atm, it is 0.25 $\text{g/cm}^2 \text{ s}$. When the burning rate is over 0.25 $\text{g/cm}^2 \text{ s}$, detonation of liquid explosives is possible.

If the impact of liquid viscosity is considered, the normal burning limit rate is Eq. 2.20.

$$u_m = \left(3\sqrt{3}g\mu\rho_2^{3/2}\delta_1^{1/2} \right)^{1/3} \quad (2.20)$$

Here, u_m is the mass burning rate ($\text{g/cm}^2 \text{ s}$) with impact of liquid viscosity; μ is the viscosity of a liquid (poise); ρ_2 is the density (g/cm^3) of gas productions; δ_1 is the density of a liquid explosive.

If the detailed burning study of nitrate ether is planned, the impact of liquid viscosity should be in consideration. The viscosity of nitroglycerine is 0.36 Poise. When $\rho_2 = 1.72 \times 10^{-4} \text{ g/cm}^3$ and $\delta_1 = 1.6 \text{ g/cm}^3$, the calculated limit rate is 0.17 $\text{g/cm}^2 \text{ s}$. The experiment rate is 0.28 $\text{g/cm}^2 \text{ s}$. The viscosity of nitroglycerine could not guarantee the stable burning. If the above values of gas production and liquid explosive are applied, stable burning is guaranteed only when the viscosity of nitroglycerine is larger than 1 poise. Plastic process of nitroglycerine enlarges the viscosity, so plastic nitroglycerine has stable burning. Experiments proved that the burning of mixtures of nitroglycerine and colloxylin (99:1) is unsteady before colloxylin becomes colloidal. After colloxylin becomes colloidal, the viscosity of mixtures of nitroglycerine and colloxylin (99:1) increases to 3.5 Poise. According to the viscosity, the burning limit rate is 0.37 $\text{g/cm}^2 \text{ s}$. So the colloidal has a stable burning rate of 0.24 $\text{g/cm}^2 \text{ s}$.

Pressure boot greatly impacts the viscosity of stable burning guarantee. At 1 atm, the required viscosity is ~ 1 Poise. The required viscosity increases dramatically when pressure is boosted. For example, the required viscosity at 100 kg/cm^2 is 1,000 times of that at 1 atm.

2.2.1.6 Burning/Combustion to Detonation of Liquid Explosives

Burning/combustion and detonation are two different concepts, but they interconnect with each other. Breaking the stable burning/combustion of explosives may lead to detonation.

When the products of liquid explosive burning reaction do not diffuse well, the reaction surface increases and the burning rate also accelerates. Once the critical value

is reached, the stability of combustion is broken, and the combustion experiences an abrupt transform to detonation. For flammable gas mixture, the shock wave is produced in the nonreacted liquids close to flame front, while the shock wave is generated in the gas products of incomplete reactions. The shock wave plays dual roles here. It increases the pressure of the liquid explosives, which is close to the burning fronts, uniforms the liquid surfaces, reduces the gaps of intersurfaces, and lowers the burning rate. The shock wave also leads to the thermal explosions of intermediates or liquid explosives of local area. The pressure jumps from thermal explosions, impacts back to unreacted liquid explosives, and leads to detonation.

The change of burning of liquid explosives to detonation experiences four stages—steady self-sustaining combustion, convection combustion, deflagration, and steady detonation. Heat transfer and initiated mechanisms are different in these four stages. Heat transfer of steady self-sustaining combustion is achieved by heat conduction. In convection combustion, the gas products inside spare surfaces ignite the inside surfaces of the gaps of liquid explosive molecules which is immigrated from the liquid bulk. It helps to increase the surface area/unit volume/mass, and the mass burning rate is about hundreds times than that of steady self-sustaining combustion. The stability of combustion is broken, and heat transfer comes true through forced convection. Heat transfer of deflagration is initiated by weak shock waves. Stable detonation is induced by strong shock waves. The total reactions accelerate, and the relative active stages have something with the physical and chemical properties of liquid explosives and the experiment conditions.

It is believed that after the stable combustion is broken, the explosion rates of explosives straighten up until stable detonation occurs. But the writer does not agree with it. In the writer's opinion, there is a deflagration stage between unsteady burning and normal detonation. It is also the new discovery from the explosion characters/features of liquid explosives.

The deflagration is stable under certain conditions. For example, when the charge diameters of the liquid explosives (e.g., $\text{H}_2\text{O}_2-(\text{CH}_3)_2\text{NNH}_2$ or $\text{N}_2\text{O}_4-\text{CH}_2(\text{NO}_2)\text{CH}(\text{NO}_2)\text{CH}_3$) are large (1,500–2,000 mm), the burning may not be stable. The deflagration stage is void and the reactions change from burning to detonation directly.

According to the experiments, when the pressure inside the containers (it is charged explosives) is lower than certain critical value P' ($P < P'$), the deflagration is stable. If $P > P'$, the deflagration changes to detonation. The exchange of deflagration to detonation is achieved in a jump range.

For the bicomposition liquid explosives or severely volatile explosives, there is no obvious deflagration stage in the change process from combustion to detonation. Convection combustion develops into detonation directly. The key feature of this change is that the detonation occurs in the fronts of convection combustion. In volatile liquids, the convection combustion develops rapidly, and forms shock waves in the front of flame fronts. The pressure of liquid surfaces accelerates the heat transfer into the inside of liquids, and leads to the heat explosion in local zone, then to the detonation of other space. If liquid explosives are charged in closed containers, it takes a time period from ignition to detonation of explosives.

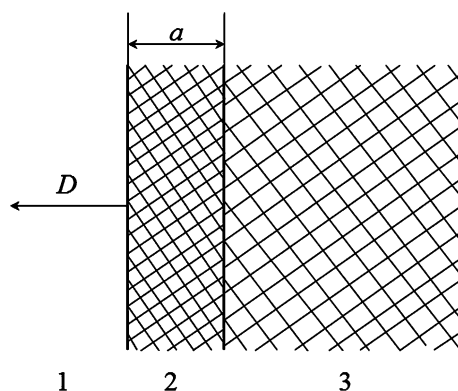


Fig. 2.4 Schematics of combustion and detonation. 1 Liquid explosives; 2 exchange zone of chemical reactions; 3 change front width of chemical reactions; D spread speed of fronts in liquid explosives

The passing distance of burning within the time period from ignition to detonation of explosives is detonation front. Under different conditions, the detonation front and degree of difficulty from burning to detonation are various.

In the combustion, detonation materials on the chemical exchange fronts shift along the media. These processing chemical exchange fronts are detonation fronts. The explosive materials react to products within the front ranges. In general, detonation is a phenomenon of fast self-spreading of detonation wave along the explosives. The spreading speed is less affected by environment. The pressure near the explosion point rises dramatically. Whether explosion is in the closed container or not, the products of explosion impact the around media drastically, then break and deform the staff around. The schematics of detonation is shown in Fig. 2.4.

The mechanisms of combustion and detonation are different. In burning, the chemical exchange fronts spread slower than the sound in liquid explosives. But in the detonation, the chemical exchange fronts shift faster than the sound in liquid explosives. Burning is spread through heat conduction, diffusion, and radiation inside the explosives. But detonation is through shock waves. Detonation waves are the shock waves following the fast chemical reactions.

These two forms of explosion of liquid explosives can interchange with each other. In certain case, combustion may transform into unstable detonation and further evolve into stable detonation.

2.2.2 Detonation of Liquid Explosives

Detonation is a process in which chemical changes occur inside explosives or flammable mixtures, whose process has some similarity with combustion. The feature of detonation is that chemical reactions do not occur within the materials at

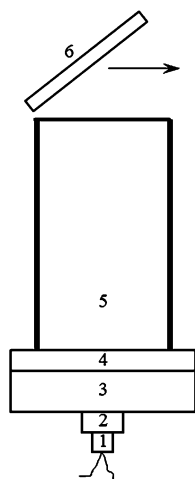
the same time, but it spreads layer by layer. Under combustion, the chemical exchange fronts shift along the media. The fronts of chemical exchange are detonation fronts. On the fronts, the explosives experience the change from reactants to products. Detonation waves are shock waves with high-speed chemical reactions. In other words, detonation is transported through shock waves.

From detonation physics, the charging and application of liquid explosives are not as wide as condensed explosives because liquid explosives are not compressible. Liquid explosives have an elusive outstanding feature, which is that the reactions of detonation absorb energy first, later release heat. The combination of exothermicity and endothermicity complicates the chemical reactions, and results in the parameter distribution characteristics of macrokinetics different from detonation characteristics of general high-energy explosives.

To study the detonation of liquid explosives and its spreading/transportation, nitromethane, nitroglycerine, diethyleneglycol dinitrate, and methyl nitrite are designed as the objectives of liquid explosives to study the chemical dynamics and the complex unsteady process of shock waves' combustion. These phenomena determine the structure of detonation wave fronts and spreading limit of detonation waves. They help to clear the flow dynamics of wave fronts, and refer suggestions for the formula of liquid explosives, study and application of equipment features. They help to improve and perfect the detonation theory.

To simplify the study, five explosives are designed. Same amount of tetranitromethane, nitroglycerine, diethyleneglycol dinitrate, methyl nitrite, and AstroliteG (hydrazine nitrate 59 %, hydrazine perchlorate 24 %, hydrazine 10 %, and methylamine 7 %) are initiated at exactly same conditions. At the same time, the same inert solvents are used to dilute the above five explosives to conduct the contrast experiments. It mainly explains the energy release of wave fronts at different time. First-hand information is obtained by this way. The equipment setup is shown in Fig. 2.5.

Fig. 2.5 Luminous equipment setup of detonation wave fronts from liquid explosives. 1 Initiation toner; 2 booster; 3 plane wave length; 4 organic glass; 5 metal pipe with liquid explosives; 6 illuminated mirror



There is steady detonation and unsteady detonation. The steady detonation has constant propagation velocity/rate; while the unsteady detonation has changing propagation velocity/rate. Generally, all detonation is steady detonation, and unsteady detonation is explosion.

When the toner initiates the detonation, in its first stage, detonation rate varies and increases gradually. This stage is unsteady detonation. Detonation experiences unsteady acceleration period and reaches the maximum steady velocity/rate/speed, and this maximum velocity is maintained until all explosives react completely.

Until now, there is little report for the study of chemical reaction zone in the detonation wave fronts of liquid explosive explosion. For a long time, the detonation mechanism of liquid explosives is considered to follow the one-dimensional model of Zeldovich, the same detonation mechanism as that of gas explosive. Although this assumption is accepted, and gets some improvement by the calculation of condensed media impact heating, the calculation and improvement are just one-sided and superficial. The detonation of liquid explosives is different from that of condensed explosives. Detonation growth process of liquid explosives is a process of weak detonation to strong detonation, from unsteady combustion/burning to steady combustion/burning, finally to detonation. Only the development of techniques and renewal of equipment help prove and clear below issues: the chemical reactions and dynamics of complex organic molecules under high pressure, the change of state function in energy releasing processes, the rule analysis of condensed medium expansion, distribution, and calculation of elastic energy and heat from chemical energy, work contribution of explosion methods and produced pressure platforms, numerical simulation of liquid explosive detonation, etc. Only after the differences from condensed explosives are settled down, the pressure profile of chemical reaction zone in the explosion of liquid explosives can be explained or calculated.

In the past, it is believed that the detonation of an explosive only has over-compressed detonation, and normal detonation, or DTT detonation from self-sustaining spread combustion/burning to detonation. Although there are detonation phenomena, which are not normally explained, only CJ detonation and its features gained the attention. Other kind of detonation is seldom being referred. If proper ignition method is used, most detonation can be transited into under-compressed detonation. "Under compressed detonation" is corresponding to the "over compressed detonation state". Earlier it was also named "weak detonation" [4, 5].

Because shock waves from liquid explosives have a stronger influence than that of condensed explosives with the same mass and especially in closed or semiclosed space, we started to investigate the characteristics of self-sustaining detonation of liquid explosives, as well as the underlying detonation mechanisms.

2.2.2.1 Detonation Mechanisms of Liquid Explosives

In the overpressure detonation, Rayleigh line represents the line of momentum and mass conservations; Hugoniot curve represents the curves of energy conservation.

The crosspoints of these two lines are S and W. But in normal detonation, Rayleigh line is tangential to Hugoniot curve (the detonation adiabatic curve). And the contact point is P. Figure 2.6 gives the relative positions of Rayleigh line and Hugoniot curve.

The contact point P corresponds to normal detonation or CJ detonation. The high crosspoint S correlates super pressure detonation. The low crosspoint W corresponds to under-compressed detonation.

N and N', which are the crosspoints of two Rayleigh lines and shock/impact adiabatic curve, correlate with the shock/impact compression condition of initiations.

Point W, which is different from S, is in the weak branch under the contact point P of the detonation adiabatic curve. Point P is also weak detonation point.

Zel'dovich founded classic detonation theory [6]. In the book "Shock Waves of Condensed Media" [7], Dremin proved that in general under-pressure detonation is not reachable using thermal dynamics and gas kinetics.

The impossibility of under-pressure detonation is discussed. Figure 2.7 shows the relative positions of detonation adiabatic curve H with balance conditions and detonation adiabatic curve k_i (k_i is the intermediates with certain amount ratio). The released energy is more if the subscript i of k_i is larger. The adiabatic curve of k_0 equals the impact adiabatic curve of the original explosives.

Fig. 2.6 The relative positions of Rayleigh line and Hugoniot curve

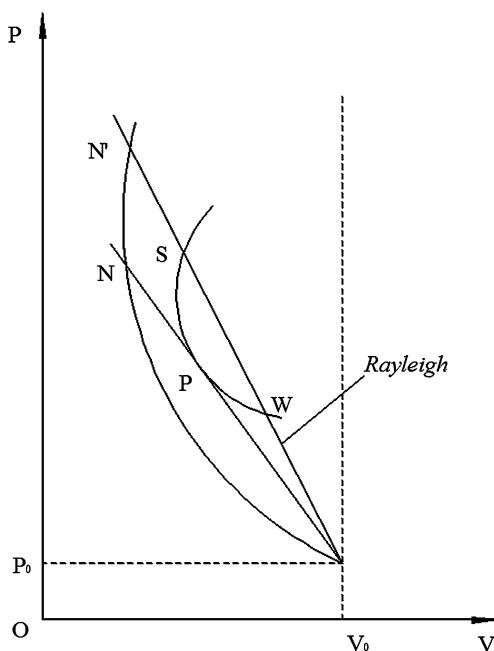
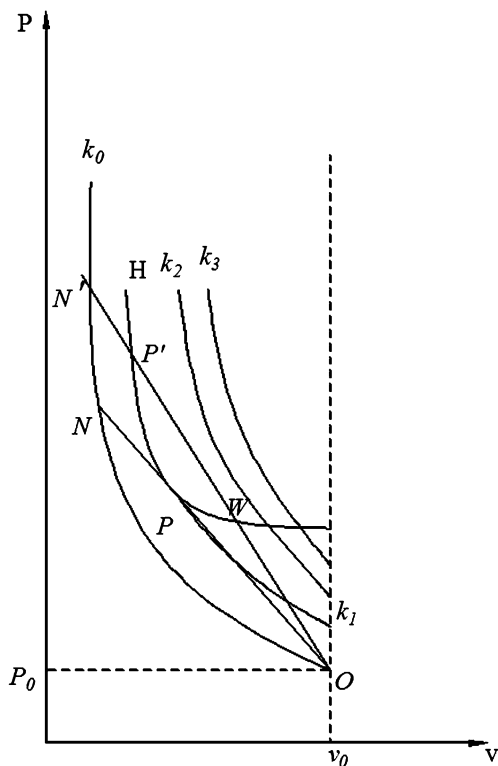


Fig. 2.7 The relative positions of balanced detonation adiabatic curve and the detonation adiabatic curves of all intermediates for the exothermic chemical reactions



According to the equation of momentum conservation, the state point, which depicts the thermodynamics of media, must shift follow one Rayleigh line until it crosses with the detonation adiabatic curve under balance.

Under the conditions, if the state points move up from O, which is the original state, it is reachable for all balance points of the weak branch (the branch under CJ point P) of detonation adiabatic curve. According to the specific reaction mechanisms, normal detonation comes true. The only mechanism is that momentum compression of explosives initiates the chemical reactions. All kinds of transportation and the transfer of radiation are negligible within the normal range of detonation shock wave fronts. The front interfaces of reaction zone are shock wave fronts, which jumps state O to Point N or N'.

Following the proceeding of detonation reactions, the pressure drops down, and the state point starts from point N or N', and moves toward the contact point P or P' along the Rayleigh line. So within the detonation wave front range, there is a chemical peak pressure increase zone of chemical peaks. The pressure distribution inside the chemical peaks depends on chemical kinetics of chemical reaction zone.

If the state point moves down from point P or P', the state point is an isentropic curve, which conflicts with the second law of thermodynamics (principle of entropy increase for any spontaneous process). If the state point moves up, it compresses the

production. But the shock wave fronts transport in ultrasound rate, all points of P and above P follow Eq. 2.21.

$$C \geq D - u \quad (2.21)$$

So compression of products is impossible.

In summary, under the study conditions, the state W, which represents all points on the weak branch of balance detonation adiabatic curve is not achievable. So under-pressure or weak detonation points do not exist. Equation 2.21 is a prerequisite for the stable transportation of detonation wave fronts.

On the other hand, ultra compression fronts are not compatible with sparse waves. Stable self-sustaining states need to meet the second prerequisite—Eq. 2.22.

$$C \leq D - u \quad (2.22)$$

Therefore, only when

$$C = D - u \quad (2.23)$$

These two prerequisites should not conflict with each other. That is the famous CJ selection rule.

In the same book, Dremine studied another condition. The reaction from k_0 to k_1 is exothermic, while the reaction from k_1 to the balance composition is endothermic. Now the smallest detonation rate is the ratio of Rayleigh line ON, which represents the denotation rate. Rayleigh line is the tangential one of the intermediate k_1 under detonation and in adiabats. The notation of exothermic energy becomes negative when it is passing this line. The detonation wave fronts spread faster than normal detonation. In other words, CJ rule (Eq. 2.23) is not applicable.

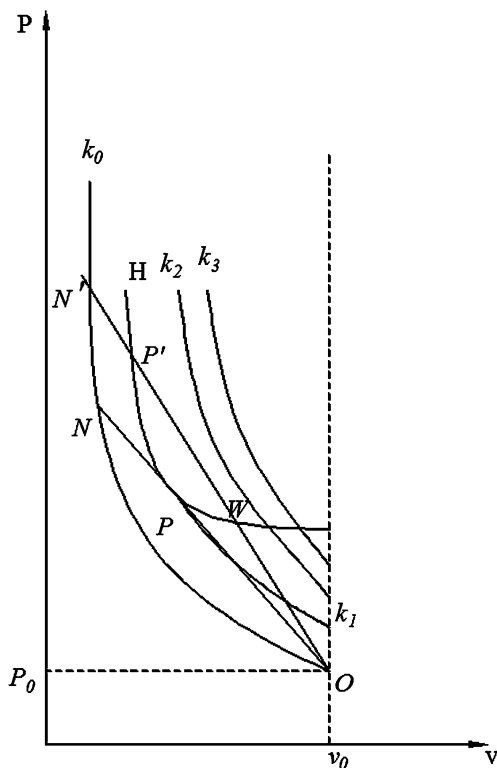
In Fig. 2.8, when the state point shifts from point N or N' along Rayleigh line to point P or P', the pressure drops, and a chemical peak shows up again. The state point cannot shift down from point P' because the intermediate/mean detonation adiabatic curve of composition k_1 is above all other detonation adiabatic line/curve. So the state point can only shift along Rayleigh line from P' to balance point S'.

If the state point starts from point P, the shift along Rayleigh line has two directions: up to point S with pressure increase, and down to point W (it corresponds with the under-pressure detonation) with pressure drop. Under suitable environmental conditions, under-pressure detonation is also possible when the pressure continuously decreases in the detonation wave range.

The detonation of liquid explosives is different from that of general condensed explosives. In common, for same mass/weight of explosives, liquid explosives do more work than condensed explosives. The under-pressure detonation of self-sustaining spreading is studied below.

More than one time, Dremine [7] referred two-stage detonation theory. The pressure inside detonation waves is determined by two-stage detonation. If the reactions inside detonation waves start slowly, and accelerate gradually, which is

Fig. 2.8 The relative positions of balanced detonation adiabetic line H , moment adiabetic line k_0 , and detonation adiabetic line k_1 with maximum exothermic energy



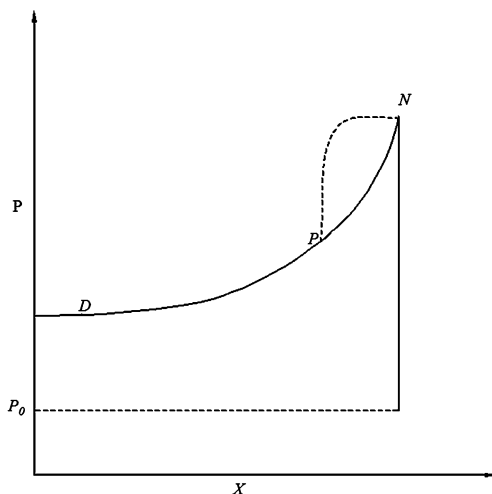
like the early stage of hot spot initiation of detonation to homogeneous detonation. The pressure distribution of two-stage detonation is the dashed curve in Fig. 2.9. If all reactions from early to final stages are faster reaction, the pressure distribution is the solid curve of Fig. 2.9.

Bdzil and Davis [8] first put forward two-stage theory, which has attracted the attention of detonation. The first fast stage releases most of exothermic detonation energy. In the second relatively slow stage, the energy released is only the remnants (e.g., 4 %). According to the above theory, if the assumption is based on the reaction rates and the calculated CJ pressure of Comp B explosives $P_H = 26.4$ GPa, and 96 % of chemical energy released in the first stage, the theory data match the experiment ones.

This study will discuss the two-stage detonation theory. The first stage is the rapid/fast reaction stage, which releases almost all energy; while the reactions of the second stage are slow, and there are possible endothermic reactions. The stable/steady under-pressure detonations would be proved.

After the detonation of liquid explosives, the detonation rate is determined by the inclination/dip angle of Rayleigh line, which is tangential to the detonation adiabetic curve with the most heat released. The detonation pressure is determined by

Fig. 2.9 The pressure distributions of two-stage detonation. The pressure distributions of normal detonation wave for *solid line* (all reactions are faster reaction from early to final stages) and *dashed line* (the origin reactions start slowly, and accelerate graduate). PD is the unsteady sparse waves



the crosspoint (W) of Rayleigh line and the adiabatic curve of detonation final products. Figure 2.10 displays the adiabatic curve of detonation final products.

In Fig. 2.10, the reactions in the first stage of detonation are fast/rapid and exothermic, while the reactions in the second stages are slow and endothermic. In the steady/stable under-pressure detonations, the inside structures of detonation waves have five parts.

Fig. 2.10 p - V plots of the under-pressure detonation W of liquid explosives

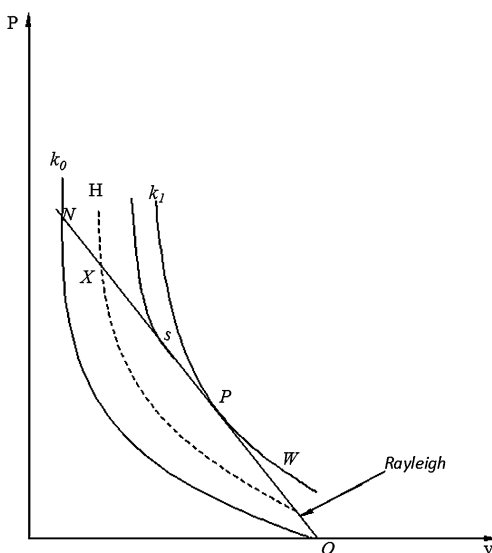
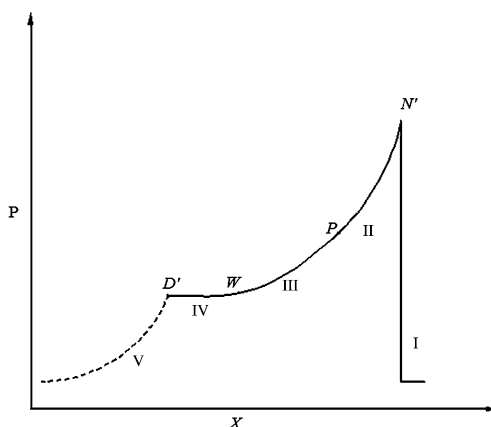


Fig. 2.11 Schematics of five parts, which compose the structure of under-pressure detonation of liquid explosives



- (1) The jump compression of shock waves reaches almost all the exchanges of detonation and energy releasing.
- (2) The endothermic reactions rapidly drop down the pressure inside detonation wave area from N to P .
- (3) After endothermic reactions, the flat transition interval of $P-W'$ forward to under-pressure detonation W .
- (4) The transportation rate is the constant self-preserving/simulating expansion area $W-D'$, which is in direct proportion to $D' - (CW + uW)$.
- (5) The area below D' is the sparse area of sputtered explosion productions.

All exchanges in detonation are shown in Fig. 2.11.

The pressure flat-forms deserve the attention, which are the key features of the constant self-preserving/simulating expansion area in the structures of under-pressure detonation. There is no pressure flat-form if detonation structures are different.

Above, the special detonation of liquid explosives is discussed. In the detonation wave range of under-pressure detonation, there is constant flow area—the flat-form of pressure. After the feature is proved, there will be potential applications in explosion industry.

2.2.2.2 Eigenvalue Detonation of Liquid Explosives

The classic detonation theory has proved that the stable/steady detonation waves of explosives propagate with CJ rate and there are sonic flows in the boundaries of detonation reactions. If the detonation waves propagate faster than CJ rate, there are subsonic flows in the boundaries of reactions. The classic detonation theory predicted that there were sustaining stable/steady detonation waves and possible special unsustaining detonation waves. The spread rates of ultrasonic waves in the boundaries of reactions are eigenvalue detonation rates.

Why eigenvalue detonation is referred here? According to Chapman and Jouguet, the founders of the classic detonation theory, the theory is completely based on the kinetic theory of gases. This is not absolutely right. The detonation theory does not have close relation with kinetic theory of gases, but also chemical kinetics. Besides the three conservation equations in the kinetic theory of gases, the equation of chemical kinetics is also being considered. In the equation, the rate of chemical reactions is important. In the kinetic theory of gases, mechanical quantities are functions of flow gradients. But in classic chemical kinetics, reaction rates, which are different from mechanical quantities, are not the functions of flow gradients, but functions of local thermal dynamic states. Mechanical quantities are different from chemical reaction rates.

How to solve the problem of combining the chemical reaction equations and the three equations of gas kinetic theory? It's extremely difficult because of the complexity of chemical reaction inside detonation area. There must be a simplified approach, which stipulates that chemical compositions react stoichiometrically according to some way, and the proceeding variable (λ_i) of stoichiometric reactions represents the complex changes of chemical compositions. This makes a chemical problem into a physical one. The simplest stoichiometric reaction is Eq. 2.24.



In the above equation, A is an explosive, B is the product of detonation, and λ is the decomposition degree of the explosive (the ratio of decomposed explosive mass to the original explosive mass). The proceeding variable λ reports the chemical changes.

The state function of detonation reaction is Eq. 2.24.

$$E = E(p, \rho, \lambda) \quad (2.25)$$

While the chemical reaction rate of detonation is Eq. 2.26.

$$r = \lambda = \frac{d\lambda}{dt} = r(p, \rho, \lambda) \quad (2.26)$$

Here, r is the chemical reaction rate; p is the pressure of detonation waves; ρ is the media density of detonation waves.

Please notice that the reaction rate is assumed to only have relationships with local state, not with flow gradients.

Von Neumann [9] studied the suspended detonation of aluminum in the oxygen gas. Al_2O_3 is not the only product because Al_2O_3 decomposes under high temperature and high pressure. So the chemical formulae have Molar reduction, and a lot of heat is given off. In irreversible reaction, Von Neumann set up the reaction in Eq. 2.27.

$$A \rightarrow (1 + \delta)B \quad (2.27)$$

The reaction is Moore fraction reduction. One molecule A reacts to $(1 + \delta)$ molecule B ($\delta < 0$). According to the mass conservation, if the molecular weight of A is MA , the molecular weight of B is $MB = \frac{MA}{1+\delta}$. The state equation changes to Eq. 2.28.

$$pV = (1 + \lambda\delta) \tilde{R}_T \quad (2.28)$$

Here, $\tilde{R} = R/M_A$, and $\tilde{R}$ is the gas constant of material A . The state internal energy function is Eq. 2.29.

$$e = m_A^0 \tilde{h}_{0A} + \left[\frac{\tilde{C}_p}{1 + \lambda\delta\tilde{R}} - 1 \right] pV - \lambda q \quad (2.29)$$

Here, $\tilde{C}_p$ is the heat capacity under constant pressure; $\tilde{h}_{0A}$ is the enthalpy of composition Molar fraction; q is the heat fraction vector frozen point.

Hugoniot curve is Eq. 2.30.

$$\left[\frac{\tilde{C}_p}{1 + \lambda\delta\tilde{R}} - 1 \right] pV - \left(\frac{\tilde{C}_p}{\tilde{R}} - 1 \right) p_0 V_0 = \frac{(p + p_0)}{2} (V_0 - V) + \lambda q \quad (2.30)$$

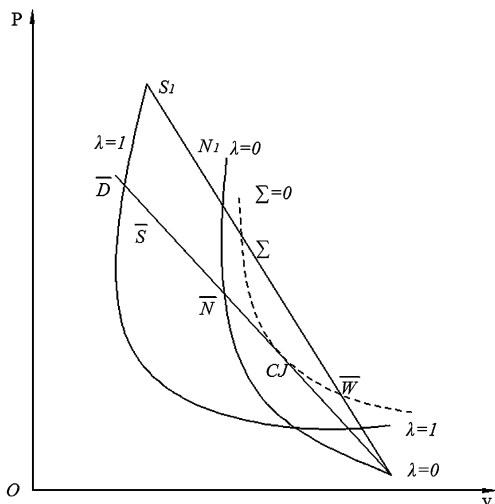
So, the envelope of *Hugoniot* curve is Eq. 2.31.

$$q = - \frac{pV\delta\tilde{C}_p}{(1 + \lambda\delta)^2 \tilde{R}} \quad (2.31)$$

Because the reaction is irreversible, $\gamma \geq 0$, and σ is not always larger than 0. When $\sigma = 0$, the curves of $\Sigma = \sigma r = 0$ are in Fig. 2.12 (Σ include all areas except Rayleigh line).

From Fig. 2.12, the curve of $\Sigma = 0$ and the frozen *Hugoniot* curve enclose into one line/curve. Because the line of $\Sigma = 0$ is the enclosed line of *Hugoniot* curve, the crosspoint of the sound track line and the curve of $\Sigma = 0$ is the tangential point (CJ) of Rayleigh line and the curve of $\Sigma = 0$. The corresponding detonation rate of Rayleigh line is $\tilde{D}$. When $D > \tilde{D}$, the mass point starts from the original state, passes shock waves, and jumps the point N of *Hugoniot* curve ($\lambda = 0$). For point N, $\eta > 0$, $\Sigma > 0$, so the mass point only moves along the Rayleigh line from the left to right, until the point Σ of Rayleigh line and $\Sigma = 0$ curve. Because $\Sigma = 0$, all parameters have extrema. When $\Sigma < 0$, the reaction shifts along Rayleigh line from the right to left, and finally reaches the final stage S1 of *Hugoniot* curve. S1 is a strong detonation point. The pressure of reacting zone/area reduces from N1 to point Σ , then increases to S1. There is a minimum pressure. The capacity V increases from N to point Σ , then reduces to S1. There is a maximum value of

Fig. 2.12 Hugoniot reaction curves of under-pressure detonation



capacity. When $D = \tilde{D}$, the mass point passes shock waves, and jumps to Point $\tilde{N}$, shifts along *Rayleigh* line to the right until CJ point. In CJ point, $\Sigma = 0$ and $\eta = 0$. (Here, σ is the constant of thermal conductivity; η is the coefficient of sound speed; $\sigma = (\partial P / \partial \lambda)_{E, v / \rho c^2}$, $\Sigma \sigma \gamma$, $\eta = 1 - (u/c)^2$; c is sound speed; u is mass velocity) [4]. Then the mass point can return to strong detonation point $\tilde{S}$ along *Rayleigh* line, or move to the right until the point $\tilde{W}$ of under-pressure detonation, and then the under-pressure detonation occurs. When $D < \tilde{D}$, the mass point starts from $\lambda = 0$ of *Hugoniot* curve along *Rayleigh* line. There is no crosspoint of *Rayleigh* line and $\Sigma = 0$ line. When *Rayleigh* line crosses the sound track line, $\eta = 0$, so $\frac{dp}{dt} = -\infty$. There is no time-independent solution.

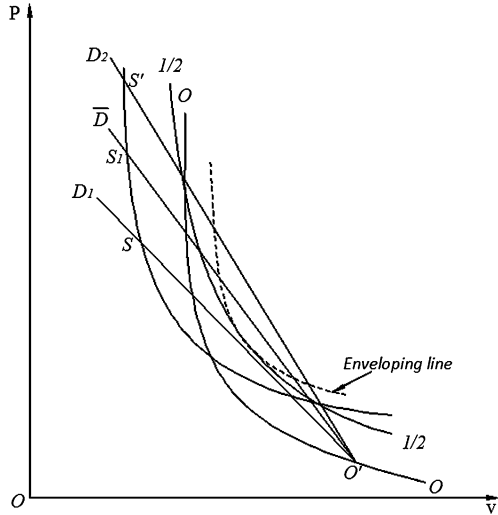
In the explosion of liquid explosives, the two prerequisites of classic under-pressure detonation are the final Hugoniot curve, (not the up boundary covered by frozen Hugoniot curve), and that *Rayleigh* line passes point $\Sigma = 0$ ($\eta = 0$), and reaches point W finally.

Figure 2.13 gives the simultaneous solution of gas dynamic equation and reaction rate equation (in plane p - λ).

In Fig. 2.13, the contact point of envelope line is at $\lambda = 1/2$. There are special situations from Fig. 2.6 through Fig. 2.13 (Fig. 2.11).

- (1) There is a special detonation rate $\tilde{D}$, which is the D value when *Rayleigh* line is tangential with the envelope curve. When $D > \tilde{D}$, the subsonic speed of *Hugoniot* curves separates with supersonic speed (Fig. 2.13) because part of *Rayleigh* line is above the envelope curve. So the detonation only occurs on the top part of *Hugoniot* curve. Following the proceeding of reactions, state point starts from shock wave point N , moves down along *Rayleigh* line until it meets envelope curve, and this point is the minimum p . Then state point of p - V

Fig. 2.13 Pathological detonation of reactions in the p - V plane



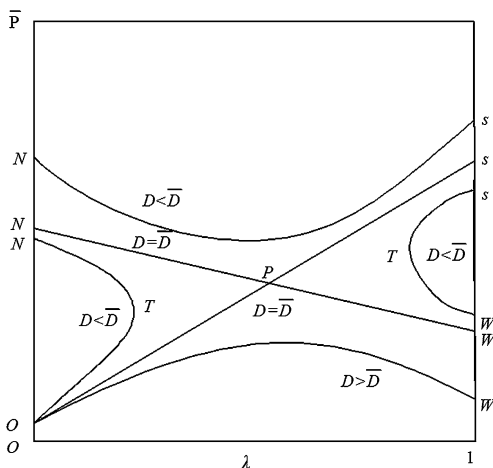
plane moves up along *Rayleigh* line, until it meets the *Hugoniot* curve ($\lambda = 1$). The shock wave of the whole flowing area is subsonic. The sparse waves from the rear degrade the flowing.

- (2) When $D = \tilde{D}$, the state point starts from shock wave point N to *Rayleigh* line. The state point line is tangential to the envelope curve. The state point reaches strong compression point S or weak detonation point W of the *Hugoniot* curve ($\lambda = 1$). The contact point P of *Rayleigh* line and the envelope line is between S and W. Von Neumann named point P as the pathological point.
- (3) For an irregular reaction, there is a $\tilde{D}$ in the reaction of the molecular amount reduction. The value of $\tilde{D}$ is related with the property of explosives (state function) and reaction rate. The under-pressure detonation occurs when $\tilde{D}$ is with certain value.
- (4) When $D < \tilde{D}$, *Rayleigh* line cannot cross or contact with *Hugoniot* curve. So there is no envelope line, and no time-independent solution.

Von Neumann explained the key features of pathological detonation with Molar reduction using one reaction in Fig. 2.14. When $D > \tilde{D}$, there are two vertical segmentations. The segmentation, which starts from point N and ends point S, is at the top. Subsonic fluctuation is at the end point S. When $D < \tilde{D}$, there are two horizontal segmentations. The reaction starts from point N, and only reaches partial reaction point T. When $D = \tilde{D}$, there is saddle-backed configuration at point P.

Figure 2.14 shows that the detonation with propagation velocity $D = \tilde{D}$ starts from the crosspoint N of the *Hugoniot* curve and shock adiabat curve. Only after passing point P is under pressure detonation point (or weak detonation point) is reached. Von Neumann named the detonation velocity as eigenvalue detonation

Fig. 2.14 The reacted pathological detonation in p - λ plane



velocity. The pathological detonation discussed above is one example of eigenvalue detonation [10–13].

Although the pathological detonation stated by Von Neumann is very interesting in theory, its application value in condensed explosives is not clear yet. The time of detonation reaction and positive pressure action of liquid explosives is far longer than that of the condensed explosives. This explained why the detonation theory of condensed explosives is not supported by the detonation theory of liquid explosives [14–16].

This book will discuss the detonation of liquid explosives—the first exothermic reaction, and the second exothermic reaction and endothermic detonation, which is one example of eigenvalue detonation. This case has application value because most of solid explosives are composed by one kind of explosives and a mixture, which deactivates adhesives. In the detonation, the deactivation of adhesives is endothermic. The eigenvalue detonation of this kind of explosives is achievable. Figure 2.15 explains the key features of the eigenvalue detonation.

In the second stage after detonation initiation, there are two irreversible reactions. The first is exothermic, and the second is endothermic. In the partial reaction Hugoniot curve of p - V plane, Rayleigh line represents momentum and mass conservation rules. $\bar{D}$ is the eigenvalue detonation velocity/speed/rate. Only when $D = \bar{D}$, under-pressure detonation point below point P is achievable.

2.2.2.3 Under-Pressure Detonation Wave of Liquid Explosives in Pistons

The piston is introduced to discuss the detonation of liquid explosives [17]. Compared to the key features of condensed explosives, the piston issues/cases of liquid explosives are a little more complex. Based on different piston rates μ_p have

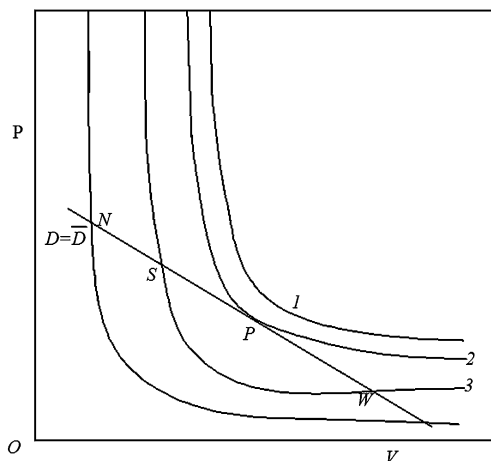


Fig. 2.15 Eigenvalue detonation curve of liquid explosives

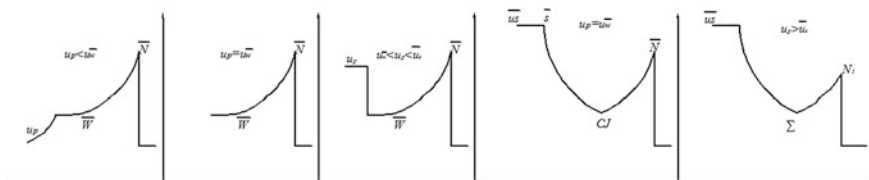


Fig. 2.16 The pressure distribution plots/curves of under-pressure detonation

different mass speed, the pressure distribution curves/plots are displayed in Fig. 2.16 [4, 5, 7].

When $\mu_p > \mu_S$, detonation waves have a minimum value in the area of strong detonation reaction area ($\Sigma = 0$), and the reaction area ends at point S1. The media is homogeneous range, and the mass velocity of uniform area is the same with point S1 (μ_{S1}). When $u_p = u_S$, the detonation is CJ one, and the reaction area ends at point $\tilde{S}$. After detonation, there is a homogeneous range with mass velocity u_S . When $u_w < u_p < u_S$, the detonation is under-pressure detonation, and the reaction area ends at point $\tilde{W}$. Because $u_p > u_w$, there are shock waves (compressing waves) to accelerate the mass to velocity u_p . Compared to the waves, detonation has supersonic velocity, so the homogeneous range is broaden continuously. If the piston velocity reduces further, there are velocity reduce mass points of sparse waves, which uniform the boundary velocities. After the waves of under-pressure detonation, the wave head point $\tilde{W}$ of sparse waves further broadens the homogeneous range.

After the above discussion, we already have enough understanding and theoretical basis for under-pressure detonation. There are two prerequisites for under-pressure detonation.

- (1) The final state *Hugoniot* curve is not the top boundary of covered area by frozen Hugoniot curve groups. Under-pressure detonation never occurs if the first prerequisite is not met.
- (2) Under-pressure detonation only occurs when Rayleigh line passes $\Sigma = 0$, at the same time $\eta = 0$.

The work passes of liquid explosives are different from that of condensed explosives. The under-pressure detonation makes detonation overpressure value larger than that of condensed explosives. So the detonation of the hydrazine-urea nitrate liquid explosive is more powerful than HMX. These are the detonation features and advantages of some liquid explosives.

2.3 Explosion Work Ability of Liquid Explosives

The high temperature and pressure products of liquid explosives violently lash against and compress the media around to make them moving, deformation, broken, and blown apart. This is the direct impact of detonation products. When the target is far from the explosion point, the damage of products is not very sharp. When explosion is in the air or water, the expansion of explosion products compresses the surrounding media, and produces shock waves. The transportation of the shock waves in the media can damage the staff/materials far away from explosion. The impact of explosion for the surrounding media has both close and far ranges.

Explosion blasting includes all mechanical impacts of explosion for the surrounding materials. The blasting of explosives are related to the packed mass, properties of explosives, the geometric figuration, and the surrounding media property (within a distance).

Study of the explosion blasting helps to evaluate the explosion characteristics and proper application of explosives, make the effectiveness of explosives complete, and supply necessary theoretical basis for packing design [18–20].

2.3.1 Work Capacity of Liquid Explosives

The shock waves of explosion in free space, the soil compression and throwing of explosion on the ground, the high-energy bubbles produced by the explosion under the water, the deformation from the engineering blasting underground or in the mines, and broken pieces produced in packing armed explosives have different damage ability and killing effects. The work of liquid explosives has various forms.

But for certain purpose, only one or several kinds of explosion are effective. The total work capacity of liquid explosives is expressed in Eq. 2.32.

$$A = A_1 + A_2 + A_3 \dots + A_n \quad (2.32)$$

Here, $A_1, A_2, A_3, \dots, A_n$ is the work of each explosive effect. A_T is the sum of all work.

The sum of all explosion effect of liquid explosives for the surrounding media is the work of explosives, or the work capacity of explosives. The capacity is also the power of explosives. It can be calculated from theory or obtained from experiments.

2.3.1.1 Ways to Express the Work Capacity of Liquid Explosives

If the work of liquid explosives to the surrounding is done through the adiabatic expansion of high-temperature and high-pressure gas products, according to the first law of thermodynamics, the decrease in the internal energy of a system is equal to the total released heat and work done to the surroundings.

$$-du = dQ + dA \quad (2.33)$$

Here, $-du$ is the decrease in the internal energy of explosive system; dQ is the heat released to the surroundings from the explosive system; dA is the work done to the surroundings.

According to the adiabatic assumption of expansion, $dQ = 0$. So Eq. 2.33 is changed to

$$dA = -du = -\bar{C}_v dT$$

After integration of A, Eq. 2.34 is obtained.

$$A = \int_{T_1}^{T_2} -\bar{C}_v dT = \int_{T_2}^{T_1} \bar{C}_v dT = \bar{C}_v (T_1 - T_2) \quad (2.34)$$

Here, T_1 is the explosion temperature; T_2 is the final temperature after cooling down (15 °C is usually used as the standard temperature); $\bar{C}_v$ is the average constant volume heat capacity of explosive products between T_1 and T_2 .

The explosion heat has below relationship.

$$Q_v = \bar{C}_v (T_1 - T_2) \quad (2.35)$$

Here, E is the mechanical equivalent of heat; Q_v is the explosion heat of an explosive; $A = EQ_v$ is the potential energy of an explosive, which is the total work

of product adiabatic expansion to cool down to the original temperature of an explosive, also the theoretical data of the work capacity of an explosive.

The work done by unlimited adiabatic expansion of explosive products until to absolute zero is the real potential energy of an explosive. But the absolute zero is nonreachable in real proceedings, and the explosion heat at absolute zero is very close to that at 15 °C. So the explosion heat at 15 °C takes the potential energy of an explosive.

$$\frac{T_2}{T_1} = \left(\frac{V_1}{V_2}\right)^{k-1}$$

or

$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{k-1}{k}}$$

The work done by the adiabatic expansion of detonation products to 1 atm pressure is expressed in Eq. 2.36.

$$\begin{aligned} A &= \bar{C}_v(T_1 - T_2) = \bar{C}_v T_1 \left(1 - \frac{T_2}{T_1}\right) = \bar{C}_v T_1 \left[1 - \left(\frac{P_2}{P_1}\right)^{\frac{k-1}{k}}\right] \\ &= \bar{C}_v T_1 \left[1 - \left(\frac{V_2}{V_1}\right)^{\frac{k-1}{k}}\right] \end{aligned} \quad (2.36)$$

If $\bar{C}_v T_1$ is replaced by explosion heat Q_v , which approximately equals $\bar{C}_v T_1$, the Eq. 2.36 becomes 2.37.

$$A \approx Q_v \left[1 - \left(\frac{P_2}{P_1}\right)^{\frac{k-1}{k}}\right] = Q_v \left[1 - \left(\frac{V_1}{V_2}\right)^{k-1}\right] = \eta Q_v \quad (2.37)$$

Here, η is the work efficiency; P_1 and P_2 are the pressures of initial and final states separately; and V_1 and V_2 are the specific volumes of initial and final state separately.

Equation 2.37 shows that the real work of detonation products is less than the potential energy of an explosive. The value of the work is related to the potential energy of an explosive, the expansion ratio $\frac{V_1}{V_2}$ of detonation products, and isentropic index k .

When the explosion products expand unlimitedly (V_2 is unlimited), the work done by explosion products equals to the potential of an explosive. If the explosion heat is higher, the work is more. When the energy potential of an explosive and the expansion ratio $\frac{V_1}{V_2}$ are fixed, a larger isentropic index k means the more complete

exchange of the potential energy to work. Because $k = 1 + \frac{nR}{\bar{C}_v}$, if $\bar{C}_v$ is smaller, k is larger. So the work A is larger.

In the evaluation of work capability of a liquid explosive, the amount of condensed products in detonation should be taken into consideration. If there are condensed products in detonation, the gas products reduce relatively, and the specific volume is small. In the expansion process, the gas products transform the internal energy into work, and its temperature drops down. The process of the internal energy from condensed products to work is that the energy of condensed products is transferred to gases, and then transformed into work. The expansion of gases is a fast process, in which it is difficult to reach the thermal balance of condensed and gas phases. Part of the energy is still stored in the condensed phase. This energy is finally lost through thermal conduction. So the measured work ability is smaller.

From the above, the explosion heat of an explosive is the conclusive parameter of work capability; while the gas products of detonation are the medium of work. More gas products and larger the specific volume, the efficiency of heat to work is higher. The specific volume of explosives also plays an important role for the work capability.

2.3.1.2 Evaluation of Work Capacity

(1) Measurement of work capacity using a lead cast method

The working capacity of explosives is usually measured/evaluated using lead cast method. This method measures the increased lead-hole volume of the lead cast in the explosion of certain explosives inside the lead hollowness. The configuration and effect are shown in Fig. 2.17.

In Fig. 2.17, the lead cast is made of fine lead. In the center of lead cast, there is a cylindrical hollowness with 25 mm diameter and 125 mm height. In experiments, the measured explosive with 10 ± 0.01 g is put in the cylindrical hollowness (24 mm in diameter) of aluminum foil. After the detonator is installed, the aluminum foil with detonator is put into the cylindrical hollowness of lead cast.

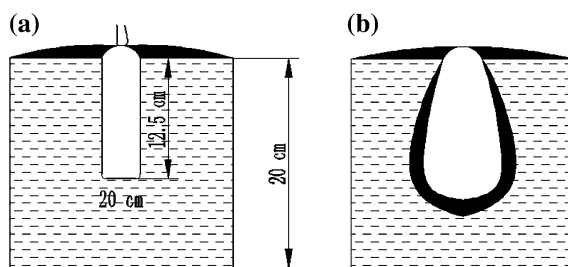


Fig. 2.17 Measurement of explosive work capacity using lead cast method. **a** The configuration of lead cast before test; **b** the effect of lead cylinder after explosion

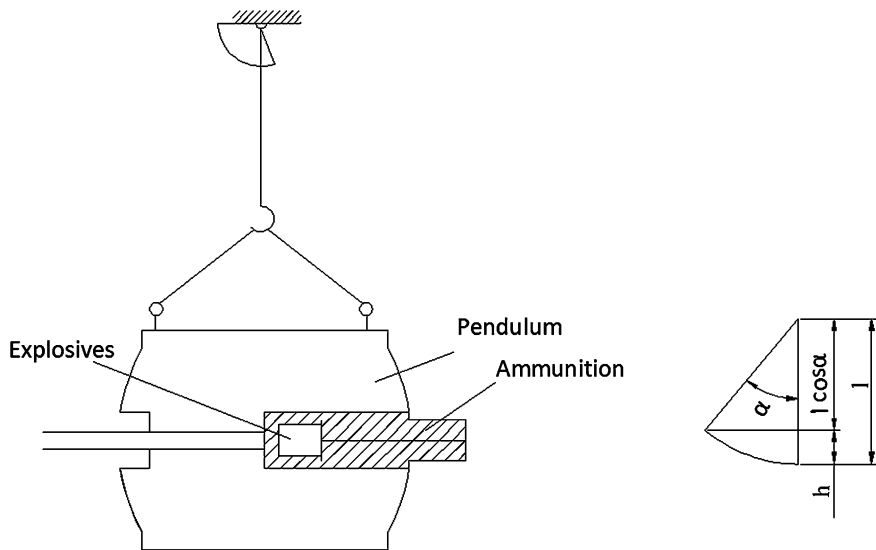


Fig. 2.18 The principle schematics of work capacity by a pendulum [18]

The remaining top space of lead cylindrical hollowness is filled by selected dry arenaceous sand to prevent the flying of explosion products. The increased volume is used to represent the work ability or capacity. Obviously, the more increased hollowness volume, the more powerful work ability/capacity. Because of the temperature effect for lead and the detonator also involves in the enlargement of hollowness, the measured data should be calibrated.

(2) Measurement of work capacity/power using a pendulum

A work capacity/power pendulum method is also named as ballistic mortar test. The measured work value is used to evaluate the relative work capacity. Its principles are in Fig. 2.18.

The explosion of liquid explosives produces high-temperature and high-pressure products. The expansion of these products works for the surrounding. Its work has two parts. One part is used to eject a bullet, and the second is to swing the pendulum to angle α with gravity center lifted up to h . The work ability/capacity of explosives is the sum of the two works.

$$A = A_1 + A_2 \quad (2.38)$$

Here, A is the work of the explosive; A_1 is the swing of the pendulum to angle α ; A_2 is the mechanical work of ejecting the solid bullet.

A_1 is the swing of the pendulum to angle α . It equals the work of lifting the gravity center of the pendulum up to h .

$$A_1 = Mgh$$

$$h = l - l \cos \alpha = l(1 - \cos \alpha)$$

So,

$$A_1 = Wl(1 - \cos \alpha) \quad (2.39)$$

Here, W is the weight of the pendulum; α is the swing angle; l is the distance of gravity center to the rotary center.

A_2 is the work of the bullet ejection. It equals the kinetic energy of the bullet when it leaves the mortar.

$$A_2 = \frac{1}{2}mv^2 = \frac{1}{2g}qv^2 \quad (2.40)$$

Here, q is the weight of the bullet; m is the mass of the bullet; v is the initial velocity of the bullet.

The pendulum and the bullet have same momentum, but their directions are reverse.

$$Mu = mv$$

In the above equation, M is the mass of the pendulum; u is the velocity of the pendulum when it starts to swing.

While $v = \frac{M}{m}u = \frac{W}{q}u$, Eq. 2.40 is rewritten in Eq. 2.41.

$$A_2 = \frac{1}{2}g \left(\frac{W}{q}u \right)^2 = \frac{1}{2} \frac{W^2 u^2}{gq} \quad (2.41)$$

If there is no energy loss in the swinging, the original kinetic energy of the pendulum equals its potential energy at the highest point.

$$\begin{aligned} \frac{1}{2}Mu^2 &= Mgh \\ u^2 &= 2gh = 2gl(1 - \cos \alpha) \\ A_2 &= \frac{W^2 g}{g} l(1 - \cos \alpha) \end{aligned} \quad (2.42)$$

So,

$$A = A_1 + A_2 = Wl(1 - \cos \alpha) + \frac{W^2}{q}l(1 - \cos \alpha) = Wl(1 - \cos \alpha) \left(1 + \frac{W}{q} \right) \quad (2.43)$$

The pendulum weight W , the bullet weight q , and the distance of gravity center to the rotary center l are fixed. The structure constant of the swing is $c = Wl \left(1 + \frac{W}{q} \right)$.

$$A = c(1 - \cos \alpha) \quad (2.44)$$

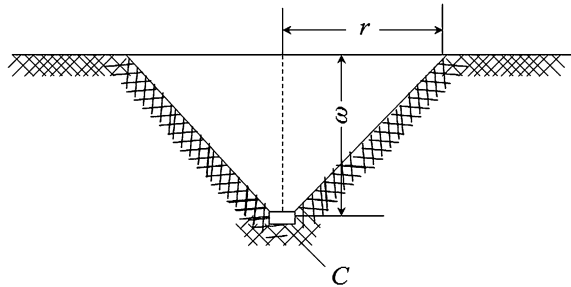
Because the structure constant c is known, the work capability/ability is directly calculated from the swing angle. In general, each country takes TNT as a standard. The ratio of the work ability/capacity of an explosive to that of TNT is its TNT equivalent. The TNT equivalent of one explosive equals A (an explosive)/ A (TNT).

(3) The work capacity/ability evaluation of an explosive by blasting cone method

Throwing blasting cone is an intuitive and convincing method to evaluate the work capability/ability of explosives. The specific volume of blasted cone is related with the properties and mass of explosives, the properties of being blasted materials, and the relative positions of media. All above factors are in consideration in the work capability evaluation of explosives using throwing blasting cone. The standard explosive and being test explosive with same mass are conducted in the exact same conditions. The work ability/capability of an explosive is roughly evaluated by comparing the volume of blasted cone to that obtained by the standard explosive.

In Fig. 2.19, the blasting cone is measured by the ratio of its radius r to depth w . $n = \frac{r}{w}$, n is index of throwing blasting action. If $n = 1$, the cone is standard throwing cone; if $n > 1$, the cone is power throwing cone.

Fig. 2.19 Throwing blasting cone



The volume of a standard cone is

$$V = 1/3 \pi r W \propto W^3$$

The relationship of a standard cone volume and the explosive mass ω is in Eq. 2.45.

$$\omega = KV\alpha KW^3 \quad (2.45)$$

The index K represents the required explosives for throwing unit volume of media in the formation of standard blasting cone, or the unconsumption of explosives. K is related with the properties of the media, and the properties and experiments with explosives.

The packing mass of explosives for power throwing blasting is calculated by below equation.

$$\omega = KW^3 f(n)$$

While,

$$f(n) = 0.4 + 0.6n^3$$

In the evaluation of the explosives by casting cone method, the places of explosion and the packing diameters are exactly the same. The variation of unconsumption displays the different work capability/ability of explosives. In the same conditions, K_1 is for explosive 1 and K_2 is for explosive 2. The work ability of two explosives is inversely proportional to their values, $A_1/A_2 = K_2/K_1$. This comparison should be conducted when the two values of n are very close to each other. The repeatability of this method is poor. Packing with relatively large amount of explosives is better.

All above three methods have their own disadvantage for measuring the work ability of explosives. There are new experiment methods in study. For example, when the explosion is under water, the new experiments include the broken dome method of spray center initiate velocity or dome method of water cylinder, the measurement of water impact energy, and bubble energy. For explosive cylinders with certain diameter, it's also a method to measure the velocity of radial displacement of cylinder shell after the explosion from one end. The earthquake method measures the highest pressure of shock waves in the water (sand, or earth), which are certain distance away from the explosion center. The experiment data of earthquake method match the calculated one very well. Because the experiment earthquake energy is linearly proportional to the mass of packed explosives, it's suitable for measuring the work ability of explosives.

2.3.1.3 Evaluation of Work Ability of Explosives by Other Methods [21, 22]

(1) The special product of explosives

The special product of explosives is the product of the explosion heat Q_v and specific volume V_0 . It has two important factors to determine the work ability of explosives, and has practical significances.

Los Alamos National Laboratory confirmed the functional relation of work capacity and mortar energy using the bullet–mortar. The function is in Eq. 2.46.

$$A_m = \frac{0.31}{850} Q_v V_0 \quad (2.46)$$

Here, A_m is the mortar energy; Q_v is the explosion heat; V_0 is the amount of gas products.

Equation 2.46 clearly shows that the bullet–mortar energy is linearly proportional with the product of Q_v and V_0 .

The explosion heat Q_v and specific volume V_0 are obtained by both experiments and calculations. In the process of obtaining Q_v and V_0 , the exact explosion chemical reactions should be fixed first because there are theoretical and empirical formations. The special product of Q_v and V_0 to evaluate the work ability of explosives matches the experiment results. For negative oxygen balance explosives, there are several different explosion reactions for one explosive. So several different product values of Q_v and V_0 would be obtained. The measurement values of explosion heat of negative oxygen balance explosives are different following the change in measuring conditions. How to choose explosion reaction equation is very important in the evaluation of explosive work ability using $Q_v V_0$ product. The released heat from secondary reactions in explosion participates blasting work, and it is also related with the work ability of explosives. Many experiments show that the product of maximum explosion heat $Q_{\max}$ and its corresponding V_m is better to express the work capability of explosives. It is that taking $H_2O + CO_2$ type explosion products sets up chemical reaction equation to calculate the maximum explosion heat $Q_{\max}$ and the corresponding specific volume V_m .

(2) Power index of work capability/ability of explosives

Power index is based on the study of relationship between explosive molecular structures and the work power. Power index method refers that the work power of an explosive is the sum of all composition functions. It puts forward power index π . The calculation of work capability/ability of an explosive using power index method is in Eq. 2.47.

$$A \text{ \% (TNT equivalent)} = (\pi + 140) \% \quad (2.47)$$

Here, π is the power index; n is the number of atoms in an explosive molecule; f is the number of characteristic groups; x is the eigenvalue of one characteristic group.

2.3.2 Improving the Work Ability of Explosives

From the theoretical expression of explosion work and extensive research, increasing the explosion heat helps to improve the working ability/capacity of an explosive. The study and application results of liquid explosives indicate that the gas products of liquid explosives are much more than condensed explosives, and when the specific volume is fixed, the work capacity of liquid explosives increases following the explosion heat. When the explosion heat increases up 100 J/gm, the work capacity raises up 5–7 %. The generalized empirical formula is below

$$A\%(\text{TNT equivalent}) = 51 + 0.05Q_v$$

Addition of hydrazine, urea perchlorate, hydrazine nitrate, or hydrogen peroxide (H_2O_2) into the formula of liquid explosives significantly increases the explosion heat. Besides above chemicals, adding the powders of aluminum, magnesium, or beryllium also raises the explosion heat of explosives. Increasing the explosion heat improves the work capacity of explosives.

Increasing the specific volumes also helps to improve the work capacity of explosives. For example, addition of hydrogen peroxide (H_2O_2) in the nitro liquid explosives, and the effect of dual oxygen (peroxide) raise the specific volumes of explosives by big percentages. This makes the work capacity improve and reachable.

The work capacity of explosives is related with oxygen balance. Improving oxygen balance of explosive is one way to increase the work capacity. This is especially important for the preparation of mixed liquid explosives. The explosives with zero oxygen balance have complete explosion reactions with maximum exothermic heat. Their work capacity is relatively high. For monomer liquid explosives, if the oxygen balance is negative, the work capacity reaches the summit with oxygen balance at -10 to -30 %. For liquid explosives with nitrate ester, nitro compounds, and nitric acid, or urea perchlorate compositions, especially when the organic fuels can undergo secondary reactions, the aluminum flakes can react with the detonation products such as CO_2 and H_2O , in some case, react with N_2 to form AlN . The oxygen balance is smaller when there is flake aluminum in liquid explosives.

Figure 2.20 displays that the relative work capacity of other explosives to TNT. The work capacity of TNT is set 100 here.

Figure 2.20 shows that the explosives with zero oxygen balance have maximum work capacity, while negative or positive oxygen explosives have lower work capacity.

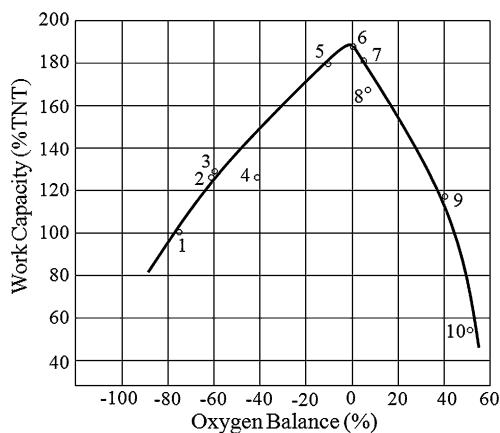


Fig. 2.20 The oxygen balance and work capacity of an liquid explosive. 1 TNT; 2 ethyl nitrate; 3 2,2-dinitropropane; 4 special Kuehl; 5 taean; 6 diethyleneglycol dinitrate; 7 NG; 8 hexanitromannite; 9 Hexanitroethane; 10 tetranitromethane

2.3.3 Brisance of Liquid Explosives [18, 19, 21, 22]

The work capacity of a liquid explosive determines its damage ability. The brisance of a liquid explosive shows its local damaging effects. Local damaging effects are also the direct effects or brisant effects. It refers the violent effect of detonation products to the surrounding media or contact staff and causes the intense damage of direct contact objects. The brisance of explosives is widely applied in rock blasting, explosion working, explosive welding, throwing objects by explosion, steel cutting of explosion, bridge destruction, broken pieces of projectile explosion, antitank, etc.

The direct effect of explosion only occurs within the close enough range. Only within close enough range, detonation products have enough energy density and high enough pressure to damage the contact objectives. The detonation theory refers that the initial stage of product expansion from condensed explosives follows state equation.

$$P\rho - \gamma = \text{Constant} (\gamma \approx 3)$$

Here, P and ρ are the pressure and density of detonation products.

For explosives with general brisance, when the expansion of detonation products increases to 1.5 times of the original radius, the pressure drops to $\sim 2,000 \text{ kg/cm}^2$, which is less effect for metal, i.e., high-intensity objects. Although the energy density of liquid explosives is higher than explosives with general brisance, their shock waves attenuate faster. The direct effect of detonation products is distinctly displayed only when the explosives contact targets or the targets are within very close range to objectives.

(1) Brisance

The ability of direct effect or brisant effect from explosive explosion is the brisance of explosives, which is another parameter to measure the blast action of explosives.

The direct effect of explosive explosion is determined by the pressure of detonation products and action time, also the pressure and momentum to the target. Actions of pressure and momentum are different under various conditions. So the pressure or momentum of detonation products is used to describe brisance.

(1) The pressure (P_2) of products in the ending of detonation reactions

The breaking surrounding media in the detonation of explosives is a result of strong impact of high-temperature and high-pressure detonation products to the media. The higher pressure of detonation products, the breaking ability to the surrounding media is more powerful. So, the brisance of condensed explosives is expressed in Eq. 2.48.

$$P_2 = 1/4\rho_0 D^2 \quad (2.48)$$

The above equation shows that the faster detonation velocity and greater density, the higher brisance. Liquid explosives are noncompressible; the density cannot be changed. Their densities and detonation velocities are constants.

For mixed or monomer liquid explosives, $D \approx A\rho_0$ when the packing density is 1.0–1.7 g/cm³. A is the detonation velocity when the density is 1.0 g/cm³. Equation 2.28 is changed to $P_2 = 1/4A^2\rho_0^3$.

The above equation fully describes that the brisance is linearly proportional to the cubic of explosive density. Increasing the density of an explosive, raises its brisance dramatically.

(2) The specific impulse affecting the target

When the affecting time of detonation products to one target is longer than its natural period of oscillation, the damage ability for the targeted object is only determined by the pressure of detonation products. When the affecting time is shorter than its natural period of oscillation, the damage is determined not only by the pressure of detonation products, but also the effecting time. The brisance of an explosive is explained by the momentum, which is related to pressure and time.

The momentum aimed on one target is the product of affecting force and affecting time (Eq. 2.49).

$$I = \int SPd\tau \quad (2.49)$$

Here, I is the momentum aimed on the target; P is the pressure on the target; S is the area; τ is the affecting time.

The momentum within unit area is the specific impulse. If the affecting area of the target S does not vary in time, Eq. 2.49 is changed to 2.50.

$$i = \frac{I}{S} = \int P d\tau \quad (2.50)$$

Once pressure is known, specific pulse is calculated.

Figure 2.21 assumes that the detonation is in one dimension; the explosive is closely contacted with the target; and the target is an absolute rigid body.

Figure 2.21 shows the pressure affecting on the target. According to one-dimensional isentropic gas dynamics, the function of pressure affecting on the target from the detonation products is Eq. 2.51.

$$P = \frac{64}{27} P_2 \left(\frac{h}{d\tau} \right)^3 \quad (2.51)$$

Here, h is the length of the packed explosive.

When the detonation ends, $\tau = h/D$ and the pressure is in Eq. 2.52.

$$P = 64/27 P_2 \quad (2.52)$$

The pressure on the target is 64/27 times of detonation pressure. The pressure on the target comes from the pressure of products, and the pressure, which is produced by moving/transportation of products with velocity u_2 . The target blocks the moving or transportation, and the shock waves are reflected, which gives the target large mobile pressure.

When $\tau = 4h/D$, $P = 1/27 P_2$, it shows that when the time is four times of explosive detonation, the pressure on the target is only 1/27 of detonation ending. The pressure decay of detonation is very fast, and the decay curve is in Fig. 2.21.

If the pressure expression (Eq. 2.51) is substituted into the integration (Eq. 2.49), the below equation is obtained.

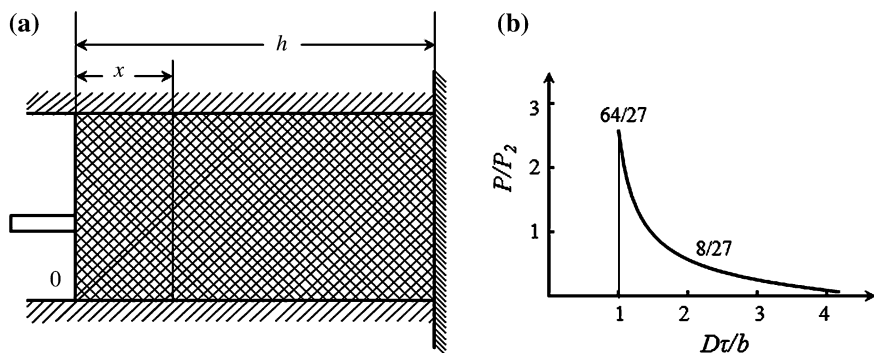


Fig. 2.21 The pressure affecting on the target. **a** Explosive properties. **b** Impulse characteristics

$$I = \int_{\frac{h}{D}}^{\infty} SP d\tau = \int_{\frac{h}{D}}^{\infty} S \frac{64}{27} P_2 \left(\frac{h}{D\tau} \right)^3 d\tau = \frac{64}{27} \left(\frac{h}{D} \right)^3 SP_2 \int_{\frac{h}{D}}^{\infty} \frac{d\tau}{\tau^3} = \frac{32}{27} S \frac{h}{D} P_2$$

Substitute $P_2 = 1/4\rho_0 D^2$ into above equation,

$$I = \frac{32}{27} S \frac{h}{D} \frac{1}{4} \rho_0 D^2 = \frac{8}{27} Sh \rho_0 D = \frac{8}{27} mD \quad (2.53)$$

Here, m is the total mass of the explosive, $m = Sh\rho_0$.

The specific impulse on the target is

$$i = 8/27 \times mD/S = 8/27 h \rho_0 D \quad (2.54)$$

The above Eq. (2.54) shows that the direct specific impulse from detonation products is linearly proportional to the explosive mass and detonation velocity (Lateral scattering is not considered). As we all know, the detonation products are isotropic scattered, and not all products affect the target. So m is not the total mass of the explosive, but the partial explosive, which directly affects the target (m is also named effect mass)

(2) Effective mass of the packed explosive

(1) Mass of packed/charged explosive for scattering in a given direction

The effective mass (ma) of packed explosive represents the partial explosive, which is equivalent of the explosive in a given direction. There are two different conditions.

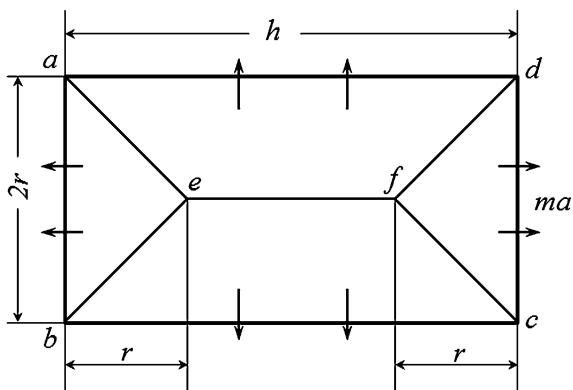
① The effective mass (ma) of packed explosives in simultaneous detonation

To effectively solve the detonation problems, the detonation is assumed to be simultaneous. The detonation reactions react at the same time, all explosives become detonation products suddenly, the detonation products occupy the original container of explosives, and all parameters of detonation products are the same everywhere. The detonation process is extremely short. Such as the detonation of explosives inside a container or projectile body, the detonation velocity is much faster than the deformation of container, so detonation is considered to be simultaneous. Calculation of the effective mass (ma) of packed explosives simplifies the detonation process, without the places of detonation and directions of transportation in consideration.

After the simultaneous detonation of cylinder packed explosives, the expansion waves diffuse into the inside of the detonation products, and the detonation products scatter in all directions. The scattering of detonation products in all directions is schematized in Fig. 2.22.

In Fig. 2.22, h is the height of packed explosives; r is the radius; ae , be , ef , cf , and df are wave fronts of expansion waves to all directions. The cone cdf is the effect packing of cylinder end. The effect packed explosive mass of the cone with height r , base area πr^2 , and volume $1/3\pi r^3$ is given Eq. 2.55.

Fig. 2.22 The scattering of detonation products after simultaneous detonation



$$ma = 1/3\pi r^3 \rho_0 \quad (2.55)$$

Here, ρ_0 is the mass density of explosives.

When $h \gg 2r$, Eq. 2.55 is exactly correct. When $h = 2r$, e and f are the same point, now the side scattering is the least.

② The effective mass (ma) of packed explosives when detonation products scatter to two ends

If the two sides of packed explosives are strong rigid shells, the detonation products only fly toward two ends rather than sides (Fig. 2.23).

When the detonation starts from the left end, the detonation products flying to the detonation end is Eq. 2.56.

$$ma = 5/9m \quad (2.56)$$

The detonation products flying to the right end is Eq. 2.57.

$$ma = 4/9m \quad (2.57)$$

ma is the effect mass of explosives.

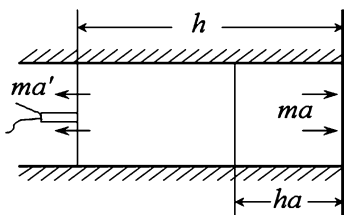


Fig. 2.23 End flying/scattering of detonation products [18]

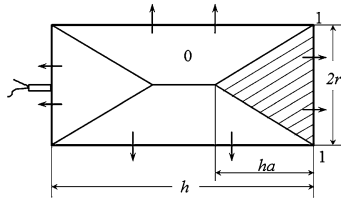


Fig. 2.24 The effective mass of packed explosives with side scattering/flying [18]

If the packed height of explosives is h , the effect height flying to the right end $ha = 4h/9$.

(2) The effective mass of packed explosives with side scattering/flying

The most common conditions are that the detonation starts from one end, the products fly/scatter in any direction (Fig. 2.24).

In Fig. 2.24, cylinder 101 is the effective mass of packed explosives with flying to the bottom. Its height is ha and radius is r .

Determination of ha is based on the assumption that the time of expansion waves transportation to the packed center equals that of detonation waves passing ha . So $\tau = r/c = ha/D$.

The velocity of side expansion waves is approximate $c \approx D/2$. And $r/(D/2) = ha/D$, so $ha = 2r$. The height of effect packed explosives equals its diameter. The volume of effective packed explosives is $1/3(2r\pi r^2) = 2/3\pi r^3$.

The mass of effective packed explosives is Eq. 2.58.

$$Ma = 2/3\pi r^3 \rho_0 \quad (2.58)$$

Substitute $S = \pi r^2$ and 2.58 into Eq. 2.54, then

$$i = \frac{8}{27} \frac{mD}{S} = \frac{8}{27} \frac{2\pi r^3}{3\pi r^2} \rho_0 D = \frac{16}{81} r \rho_0 D \quad (2.59)$$

When the packing of explosives is long enough and detonation starts from one end, the specific impulse of the bottom is $i = \frac{16}{81} r \rho_0 D$.

(3) The effective height of packed explosives

When the height of packed explosives is not long enough, the effective packed explosives flying to the base are not guaranteed to be cone. When the effect height $h = 3r$, according to the theory of two ends flying/scattering, the packed height to the bottom is $4/9h = 4/9(3r) = 4/3r$. This height is shorter than effect height $2r$, which is the theoretical value (Fig. 2.25).

Figure 2.25 describes that the measurement of brisance without enough packing height does not need to take the packed mass into consideration. But the effective packed height should meet $4/9h = 2r$.

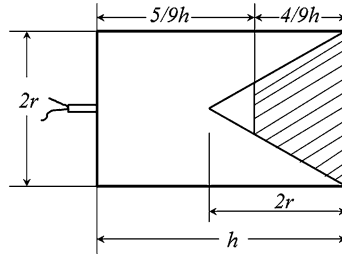


Fig. 2.25 The effective packed explosives when the height is not enough [18]

So,

$$h = 9/2r = 2.25d \quad (2.60)$$

The effective height is 2.25 times of diameter.

When the packed height is longer than the effective height, the effective packing mass for base does not increase. The effective mass is the volume of a cone with base diameter. If the packed height is shorter than the effective height, the effective packed explosive mass is a truncated cone. The relative packed masses ma under these two conditions are Eqs. 2.61 and 2.62, separately.

$$h \geq 4.5r, ma = \frac{2}{3} \pi r^3 \rho_0 \quad (2.61)$$

$$h < 4.5r, ma = \left(\frac{4}{9}h - \frac{8}{81} \frac{h^2}{r} + \frac{16}{2187} \frac{h^3}{r^2} \right) \rho_0 \quad (2.62)$$

(3) Measurement of brisance

The measuring methods for the brisance of liquid explosives are similar to that of condensed explosives. The measuring difficulty is larger because of the noncompressibility of liquids. The writer/author measured the brisance of liquid explosives using the setup of Fig. 2.26, and summarized a set of methods for evaluating the brisance of liquid explosives.

In Fig. 2.26, the plastic shell is hard polyethylene with 1.0 mm thick. The thickness of the bottom, which is in contact with a lead cylinder, is 0.015 mm. The dissipative energy of breaking the plastic shell is negligible.

Fig. 2.26 Setup for brisance measurement of liquid explosives



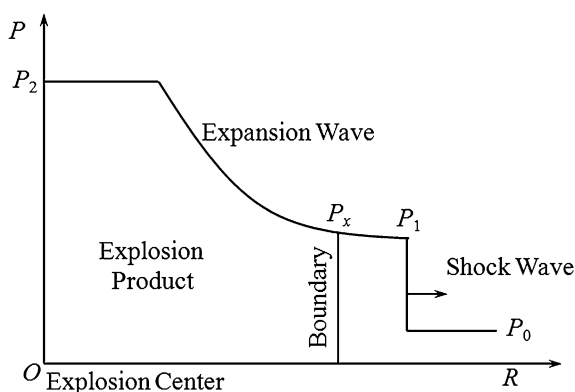
2.4 Explosion Impact of Liquid Explosives

2.4.1 Explosion Impact of Liquid Explosives in Free Space

2.4.1.1 Detonation of Liquid Explosives in Free Space

When the explosion of liquid explosives occurs in free space, the detonation reactions release large amount of energy in the form of pressure, and the gas products expand rapidly to the surrounding. This results in the pressure of gas products and temperature increase of local areas, which impacts the surrounding media by high temperature and high pressure in the explosion direction, presses the air and forms air shock waves. Following the further expansion of detonation products, the air shock waves increase in their layer thickness. The pressure distributions of detonation products and air shock waves are shown in Fig. 2.27.

Fig. 2.27 Pressure distributions of detonation products at initial expansion stage



Here, P_0 is the air pressure without disturbance; P_1 is the pressure of air shock wave fronts; P_x is the interface pressure of detonation products and air.

The pressure of detonation products drops rapidly in the expansion process. When $P \geq P_k \approx 2,000 \text{ kg/cm}^2$, the detonation products of general explosives in their initial expansion follow the rule of $P = A\rho^3$. The pressure changes following the cubic density. The density of detonation products reduces rapidly following the radius increase. If the packing geometry of explosives is spherical, $\rho \propto r^{-3}$, hence,

$$P \propto r^{-9}$$

When the radius of detonation products increases up 1 time, the pressure drops to $\frac{1}{29} \approx \frac{1}{500}$.

The limiting volume of detonation products is the volume of products when their pressure drops to the pressure of surrounding media. The volume of detonation products may be roughly estimated using the below method. When the pressure of detonation products $P < P_k$, the expansion process follows the rule of $P = A\rho^k$ (here, $k = 1.2-1.4$).

The volume of detonation products is V_L at pressure P_0 .

$$P_0 V_L^k = P_k V_k^k = C \quad (C \text{ is a constant})$$

$$\frac{V_L}{V_0} = \frac{V_k}{V_0} \frac{V_L}{V_k} = \left(\frac{P_2}{P_k} \right)^{1/3} \left(\frac{P_k}{P_0} \right)^{1/3} \quad (2.63)$$

Here, P_2 is the initial average pressure of detonation production.

If $P_2 = 100,000 \text{ kg/cm}^2$, $P_0 = 1 \text{ kg/cm}^2$, $P_k = 2,000 \text{ kg/cm}^2$,
when $k = 7/5 \frac{V_L}{V_0} = 50^{1/3} \times 2000^{5/7} = 800$;

when $k = 5/4$, $\frac{V_L}{V_0} = 50^{1/3} \times 2000^{4/5} = 1600$.

For most of explosives, the volumes of detonation products which expand to pressure P_0 is about 800–1,600 times of their original volumes. If the limit volume of detonation products is known, the limit impact distance can be calculated. The geometry of explosives is assumed to be a sphere, so

$$\frac{V_L}{V_0} = \left(\frac{r_L}{r_0} \right)^3 \quad \text{or} \quad r_L = r_0 \left(\frac{V_L}{V_0} \right)^{1/3} \quad (2.64)$$

Here, V_L is the limit volume of detonation products; V_0 is the volume of explosive sphere; r_L is the limit radius of detonation products; r_0 is the radius of explosive sphere.

Most of experiments show that the volume of detonation products from liquid explosives is about 20–60 % larger than that of condensed explosives. Under standard condition, the expansion ratio is 920–1,600. For a spherical 1 kg liquid explosive with density 1.58 g/cm^3 , the r_L is calculated below.

When $V_L = 920 \text{ L/kg}$, $r_L = \sqrt{\frac{920}{1.58}} \times r_0 = 3.81r_0$

When $V_L = 1,000 \text{ L/kg}$, $r_L = 11.7r_0$

For sphere explosives, the direct effect/impact range of detonation products is about $10\text{--}12r_0$. For cylinder explosives, the direct effect/impact range is about 30 times of the radius. The detonation products decay very fast in unlimited space, the effect range for the target is very close.

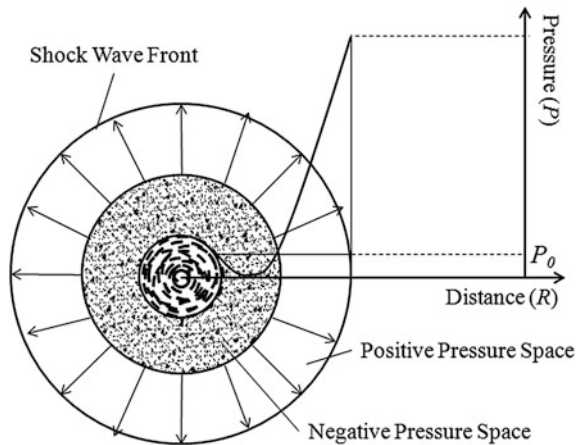
Because of the inertia, the expansion of detonation products does not stop at pressure P_0 until it reaches the maximum value of expansion (about $135\text{--}145V_L$). Now the average pressure of detonation products is lower than undisturbed air pressure P_0 . The surrounding air in return compresses the detonation products and increases their pressure. By the same reason of inertia, the maximum pressure of products is a little higher than P_0 . The second and multiple expansion-being compression pulsations occur. The pulsation and whirlpool in the intersurfaces blur the intersurface, and finally the detonation products and air mix together.

When the detonation products stop expanding and contract back, the air shock waves separate with the detonation products and propagate independently. For the detonation of liquid explosives, the separation occurs at about the place, which is $10\text{--}15r_0$. Now the pressure of air shock wave fronts is $10\text{--}20 \text{ kg/cm}^2$ and the propagation velocity is $1,000\text{--}1,400 \text{ m/s}$. The mass velocity after fronts is $800\text{--}1,400 \text{ m/s}$. Figure 2.28 gives the pressure distribution of shock waves.

In Fig. 2.28, the center is the position of liquid explosives. The middle is the detonation products with median pressure. The most outside is the air shock wave front, whose pressure is the highest. The pressure of the compression area after the wave front decays faster. It is sparse area when the pressure is less than 1 atm.

The geometries of packed/charged explosives also impact the air shock waves differently. If the measurements of packed/charged explosives are very similar in all directions, the packed/charged geometry impact direction differently in the area, which is contactable with or very close with explosives. For a little far away places,

Fig. 2.28 Pressure distributions of pulse waves in the detonation of liquid explosives



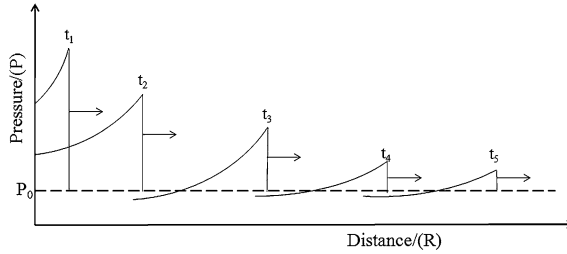


Fig. 2.29 Transportation of pulse waves in the explosion of liquid explosives

the average impact is equivalent to that of spherical charge/packing explosives. If the charge or packing is obviously larger in one dimension than other dimensions, the impact within two times of two small dimensions is equivalent to the cylindrical charge/pack. When it is far away, such several times of the longest charge/packing dimension, the impact is equivalent to that of spherical charge/packing. This is because the air shock waves are gradually homogenized in all directions.

The high-temperature and high-pressure detonation products of liquid explosives expand rapidly. This expansion is regarded as the piston motion in a pipe, which compresses the surrounding media air and increases its pressure. After the air detonation waves separate from the detonation products, the detonation waves transport in the air following what in Fig. 2.29.

In Fig. 2.29, $t_1, t_2, \dots$ are the reaching time of shock waves. Figure 2.29 indicates that the positive pressure area is broadening following the transportation of air shock waves. Because the shock wave front transports at supersonic velocity D , while the shock wave end does at sound velocity c_0 , and $D > c_0$, the positive area broadens, following the transportation of air shock waves. In Fig. 2.29, the pressure of wave front and transportation velocity D drop faster. There are several reasons for the rapid dropping of pressure and transportation velocity. First, the shock waves expand spheroidally, their surface area of shock wave fronts is continuously growing, but the energy passing the unit area shock wave fronts decrease. Second, the average energy of the air shock wave fronts declines. Beside that, when the shock wave passed the air, the temperature of the air increases, so part of shock wave energy is used to heat the air. Based on above reasons, in the transportation process of air shock waves, the pressure of wave fronts declines faster, and decays into sound wave finally.

2.4.1.2 Parameter Calculation of Shock Waves Produced by Detonation of Liquid Explosives in Free Space [23, 24]

The detonation products just impact within short ranges, air shock waves create the main damage of explosion of liquid explosive in free space. The damage and killing effect of air shock waves are more violent in the closer ranger with smaller impact

area; the effect is weak if far away from the explosion center, but the effective area is larger. For an explosion in the air, if the super pressure of shock waves is 0.2 kg/cm^2 with total area 100, the area with super pressure $>20 \text{ kg/cm}^2$ is only 1.3 %; while the area with super pressure $2\text{--}20 \text{ kg/cm}^2$ is about 6.7 %. For more than 92 % area, its super pressure is $0.2\text{--}2 \text{ kg/cm}^2$. Nonetheless, we cannot underestimate the damage ability of shock waves. When shock waves impact the building in large area, the super pressure $0.2\text{--}2 \text{ kg/cm}^2$ of wave fronts has enough killing capacity for human and damage for glasses of buildings and buildings with wood-brick structure. In general, the shock waves from liquid explosives are stronger than that of condensed explosives, so liquid explosives are more damageable. The parameter change law study of shock waves in the explosion is a must to study the damage capacity of explosives.

(1) Explosion similarity law of air shock waves

The shock wave impacts from same explosives with different masses follow the geometry similarity law in the space before the shock waves meet the boundaries or obstacles. For an explosive with packed radius r_1 , the super pressure of shock wave front at R_1 is ΔP ; and if the second explosive with r_2 , the super pressure of shock wave front at R_2 is ΔP . These two explosives are similar in geometries of packing. The geometric similarity rate is of practical importance for the design of engineering. The experiments can be studied with small amount of explosives and measure all parameters in free field. The conditions of explosion with large amount explosives can be calculated/predicted based on the experiments. It helps to reduce the experiment numbers and lower the cost of experiments.

In all the shock wave parameters, if the super pressure of shock wave front is known, all other parameters can be calculated according to the relationship of shock waves. Once the dimension relationship is fixed, the relationship of shock wave parameters and explosive packing is reachable.

For the explosion of liquid explosives in air, the fundamental physical quantities, which influenced the pressure of shock wave fronts, are detonation heat Q_v , packed density ρ_0 of an explosive, packed radius r , distance to explosive's center R , air pressure P_a , and its origin density ρ_a . After ignoring the viscosity and thermal conduction of air, the super pressure of air shock wave is a function of all parameters (Eq. 2.65).

$$\Delta P = f(Q_v, \rho_0, r, R, P_a, \rho_a) \quad (2.65)$$

If the distance to an explosive's center R is taken as unit to measure the distance, air pressure ($P_a = 1.0332 \text{ kg/cm}^2$) to measure the pressure, and air density ($\rho_a = 1.25 \times 10^{-3} \text{ g/cm}^3$) to measure the density, the distance to an explosive's center, air origin density, and origin pressure are all 1.

$$\bar{R} = 1 \bar{p}_a = 1 \bar{\rho}_a = 1 \quad (2.66)$$

The super pressure of air shock waves, packed radius, packed density, and detonation heat of explosives are displayed below, separately.

$$\begin{aligned} \Delta \bar{p} &= \frac{\Delta P}{p_a} \\ \bar{\rho}_0 &= \frac{\rho_0}{\rho_a} \\ \bar{r} &= \frac{r}{R} \\ \bar{Q}_v &= \frac{Q_v}{p_a / \rho_a} \end{aligned} \quad (2.67)$$

All these are ratio without any unit. Now it's time to infer and prove the detonation heat.

$$\bar{Q}_v = \frac{Q_v}{R^\alpha p_a^\beta \rho_a^\gamma} \quad (2.68)$$

The denominator in Eq. 2.68 is the product of unit physical quantities R , P_a , and ρ_a after potential operations to get the values of α , β , and γ . If the dimension of length is L , mass is M , time is T , the dimensions of Q_v , R , P_a , and ρ_a are as in below equations separately.

$$\begin{aligned} [Q_v] &= L^2 T^{-2}; \\ [R] &= L; \\ [p_a] &= M L^{-1} T^{-2}; \\ [\rho_a] &= M L^{-3} \end{aligned} \quad (2.69)$$

Equation 2.68 becomes 2.70.

$$L^2 T^{-2} = L^\alpha (M L^{-1} T^{-2})^\beta (M L^{-3})^\gamma = L^{\alpha - \beta - 3\gamma} M^{\beta + \gamma} T^{-2\beta} \quad (2.70)$$

Compare the powers of L , M , and T , so

$$\begin{aligned} L : 2 &= \alpha - \beta - 3\gamma \\ M : 0 &= \beta + \gamma \end{aligned}$$

$$T : -2 = -2\beta \quad (2.71)$$

The solution for above simultaneous equations is Eq. 2.72.

$$\begin{aligned} \alpha &= 0; \\ \beta &= 1; \\ \gamma &= -1 \end{aligned} \quad (2.72)$$

The relations of all physical quantities are certain, which do not change after their units vary. So the function of $\Delta\bar{P}$, $\bar{Q}_V$, $\bar{\rho}_0$, $\bar{r}$, $\bar{R}$, $\bar{p}_a$, and $\bar{\rho}_a$ is similar to the function of ΔP , Q_V , ρ_0 , r , R , p_a , and ρ_a .

$$\Delta P = f(\bar{Q}_V, \bar{\rho}_0, \bar{r}, \bar{R}, \bar{p}_a, \bar{\rho}_a) \quad (2.73)$$

Substitute 2.66 and 2.67 into 2.73,

$$\frac{\Delta P}{p_a} = f\left(\frac{\bar{Q}_V}{\bar{p}_a/\bar{\rho}_a}, \frac{\rho_0}{\rho_a}, \frac{r}{R}, 1, 1, 1\right) \quad (2.74)$$

In Eq. 2.74, the three constants 1 do not have any special meaning, so the dimensionless Eq. 2.75 is obtained.

$$\frac{\Delta P}{p_a} = f\left(\frac{\bar{Q}_V}{\bar{p}_a/\bar{\rho}_a}, \frac{\rho_0}{\rho_a}, \frac{r}{R}\right) \quad (2.75)$$

The function f is still not clear yet. Its determination needs the support of more experiments. But Eq. 2.75 is much simpler than 2.65. By using dimensionless parameters, the three arguments are reduced, and it decreases the experiment work. If the experiments are conducted under the same conditions using same explosive with same packing density, $\frac{\bar{Q}_V}{\bar{p}_a/\bar{\rho}_a}$ and $\frac{\rho_0}{\rho_a}$ are constants. Equation 2.75 is simplified as Eq. 2.76.

$$\frac{\Delta P}{p_a} = f\left(\frac{r}{R}\right) \quad (2.76)$$

After multiple experiment, only if

$$\frac{r_1}{R_1} = \frac{r_2}{R_2} = \frac{r_3}{R_3} = \dots = \text{Constants} \quad (2.77)$$

All measured super pressure are the same, this is the explosion geometric similarity law of air shock waves.

The above geometric similarity law is not applied for the explosive with different packing densities. If the super pressure of shock waves from explosive W_1 is ΔP at R_1 , and the super pressure of shock waves from explosive W_2 is ΔP at R_2 , Eq. 2.78 is established.

$$\frac{R_1}{R_2} = \sqrt{[3]} \frac{W_1}{W_2} \quad (2.78)$$

ΔP is a function of $\frac{\sqrt{[3]}W}{R}$, so

$$\Delta P = f\left(\frac{\sqrt{[3]}W}{R}\right) \quad (2.79)$$

The above geometric similarity law is applied for the same explosives with different packing density, but it is not applied for explosives with different detonation heat. For explosives with different detonation heat, even with same packing mass, the explosion effects are different at the same distance. Because of their explosion heat is similar, $\frac{\sqrt{[3]}E}{R}$ is used as a parameter. Here, E is the energy of explosion, which is transferred into the shock waves.

$$\Delta P = f\left(\frac{\sqrt{[3]}E}{R}\right) \quad (2.80)$$

Energy similarity law is applied not only in different kinds of explosives, but also in different kinds of explosions. In general, the function $f\left(\frac{\sqrt{[3]}E}{R}\right)$ is extended to a polynomial 2.81.

$$\Delta P = A \frac{\sqrt{[3]}E}{R} + B \left(\frac{\sqrt{[3]}E}{R}\right)^2 + C \left(\frac{\sqrt{[3]}E}{R}\right)^3 \quad (2.81)$$

The constants A, B, and C are obtained from experiments. $E = WQ_V$, for TNT, $Q_V = 4180$ J/g, substitute this into 2.81, Eq. 2.82 as below.

$$\Delta P = A_1 \frac{\sqrt{[3]}E}{R} + B_1 \left(\frac{\sqrt{[3]}E}{R}\right)^2 + C_1 \left(\frac{\sqrt{[3]}E}{R}\right)^3 \quad (2.82)$$

Parameter $\frac{\sqrt{[3]}E}{R}$ is also one of the parameters of energy similarity. For all explosives, all their mass can be changed into TNT equivalents.

$$W_E = W \frac{Q_V}{Q_{VINT}} \quad (2.83)$$

Here, W is the mass of an explosive; Q_V is the detonation heat of an explosive; Q_{VTNT} is the detonation heat of TNT (4,180 J/g); W_E is the TNT equivalent of an explosive.

(2) Super pressure calculation of shock waves from explosions of liquid explosives

When spherically packed TNT explodes in free space, the super pressure calculation of shock waves follows the below equations.

$$\Delta P = 0.84 \frac{\sqrt{[3]E}}{R} + 2.7 \left(\frac{\sqrt{[3]E}}{R} \right)^2 + 7 \left(\frac{\sqrt{[3]E}}{R} \right)^3$$

or

$$\Delta P = \frac{0.84}{\bar{R}} + \frac{2.7}{\bar{R}^2} + \frac{7}{\bar{R}^3} \quad (2.84)$$

$$1 \leq \bar{R} \leq 10-15$$

$\bar{R} = \frac{R}{\sqrt{[3]W}}$ is the contrast distance.

If the explosive is on the ground, the energy transferred into the ground is negligible. All energy is approximately transferred into the hemispherical space. For an open space, the reflection waves are also negligible. For the explosion on the ground, $W_E = 2W$. Substitute this into 2.84, Eq. 2.85 is obtained.

$$\Delta P_E = \frac{1.06}{\bar{R}} + \frac{4.3}{\bar{R}^2} + \frac{14}{\bar{R}^3} \quad (2.85)$$

Here, ΔP_E is the super pressure of shock waves when explosion occurs on the ground.

If the unit of R is meter, and W is kg, all calculated results are basic data for theoretical shock waves. The relationship of shock wave super pressure and distance is in Table 2.2. For all explosives, their explosion heats are TNT equivalents. The application range of Eq. 2.85 is between 1 and 10–15. When $\bar{R} < 1$, the errors are larger.

The packed geometry of explosives impacts the super pressure of shock waves in some degree. Probably because in explosion, the transportation forms of detonation products are impacted by the geometries of explosives. The impaction of packed geometries is in Table 2.3.

(3) Calculation of action time and specific impulse in the positive pressure area

The action time t_+ in the positive pressure area of liquid explosive explosion is another parameter of air shock waves, which play an important role for the damage of targets. Like the determination of super pressure ΔP , t_+ is an empirical formula using similar principle and experiments.

Table 2.2 ΔP and $\bar{R}$ in the air pulse waves [18]

$\bar{R} = \frac{R}{\sqrt{[3]W}}$	ΔP_E (kg/cm ²)	ΔP_A (kg/cm ²)	$\bar{R} = \frac{R}{\sqrt{[3]W}}$	ΔP_E (kg/cm ²)	ΔP_A (kg/cm ²)
15	0.094	0.07	3.0	1.35	0.85
12	0.126	–	2.75	1.63	–
10	0.163	0.118	2.50	2.00	1.21
9	0.19	–	2.0	3.35	1.99
8	0.227	0.161	1.8	4.21	2.50
7	0.281	–	1.6	5.75	3.29
6	0.36	0.247	1.4	7.94	4.52
5	0.469	0.332	1.3	9.73	5.43
4.5	0.602	–	1.2	12.00	6.60
4.0	0.743	0.488	1.10	15.00	8.20
3.5	0.981	–	1.0	19.4	10.54

Table 2.3 Figurations and ΔP [18]

Explosive	Configuration geometry	Packed mass (kg)	ΔP (kg/cm ²)	
			$\bar{R} = 1$	$\bar{R} = 10$
TNT	Rectangular	0.23	29.9	0.094
TNT	Cylinder	1.81	18.5	0.114
TNT/PETN (50/50)	Cylinder	3.6	20.7	0.112
TNT/PETN (50/50)	Sphere	1.71	11.9	0.124

Note T/P = TNT/PETN from the above table, it is clear that the places near explosives are influenced by the geometries of explosives; the far away place is less influenced by it

The calculation uses TNT sphere as a reference, and the extension calculating of explosion in the air. When TNT explodes,

$$t_+ = 1.5 \times 10^{-3} \sqrt{\bar{R}} \sqrt{[6]W} \quad (2.86)$$

If the explosion is on the ground, $W_E = 2 W$.

$$t_+ = 1.7 \times 10^{-3} \sqrt{\bar{R}} \sqrt{[6]W} \quad (2.87)$$

Here, the unit of action time t_+ is millisecond (ms); the mass W is gram (g); the distance R is meter (m).

The conclusions from the several hundred measurements suggest that the reaction time of positive pressure shock waves from condensed explosives is generally 2–10 ms; from the liquid explosives is 15–49 ms, for certain special liquid explosives, the action time reaches 80 ms. In certain degree, the detonation velocity/rate is lower than condensed explosives, but the impact capacity of liquid explosives are higher than condensed ones.

The specific impulse (i) is directly determined by the super pressure ΔP of air shock wave fronts and the reaction time (t). Because the calculation is much complex, it is obtained using empirical formulations of experiments.

$$i = A \frac{W^{2/3}}{R} = A \frac{W^{1/3}}{\bar{R}} \quad (R > 12r) \quad (2.88)$$

$$i = B \frac{W^{2/3}}{R^2} = B \frac{W^{1/3}}{R^2} \quad (R \leq 12r) \quad (2.89)$$

Here, r is the radius of an explosive; the unit of specific impulse i is kgs/m^2 . For the explosion of TNT in unlimited space, $A = 40$, and $B = 25$. For all other explosives, A and B need calibration.

$$i = A \frac{W^{2/3}}{R} \sqrt{\frac{Q_{vi}}{Q_{v\text{TNT}}}} \quad (2.90)$$

Here, W is the mass of an explosive; R is the distance to explosion center; Q_{vi} is the detonation heat of explosive i ; and $Q_{v\text{TNT}}$ is the detonation heat of TNT.

2.4.1.3 The Damage of Air Shock Wave for the Target in the Explosion of Liquid Explosives in Free Space

The shock waves, which are produced from explosion of liquid explosives in free space, damage and fracture the surrounding targets (for example, building, equipment, and human) in certain degrees. But the damage and fracture of various targets from the shock waves of explosives are a very complex process. It is related with not only the impact of shock waves, but also the shape, rigidity, flexibility of the targets. The loads and damage of buildings from shock waves are determined by below factors.

- (1) the super pressure ΔP of shock wave fronts
- (2) the action time of shock wave and the pressure change
- (3) the positions of buildings (the relative relation of buildings and shock wave fronts, e.g., the fronts of shock wave are parallel or perpendicular with the buildings)
- (4) the sizes and figurations of buildings
- (5) the vibration periods of the buildings

The work capacity of explosives determines damage of explosion. They are different following the change of explosive, packed mass, the surrounding media. And the damage is also different if the distance to the explosion center varies.

The work capacity and the related damage increase following the potential capacity and specific volume become larger. When the explosive properties and packed mass are given, the effect action distance is related with the geometry and detonation methods.

According to isentropic law of detonation production expansion, the theoretical work capacity of an explosive is below.

$$dA = -dE = -C_v dT$$

Because

$$C_v = \frac{nR}{k-1}$$

So

$$A = \frac{nRT_D}{k-1} \left(1 - \frac{T_1}{T_D} \right) \quad (2.91)$$

If A is the work of per kilo gram explosive, and $Pv^k = c$ (constant), $Tv^{k-1} = \text{constant}$ and $T^k p^{1-k} = \text{constant}$, the final equation of work is eq. 2.92a

$$A = \frac{F}{k-1} \left(1 - \frac{T_1}{T_D} \right) = \frac{F}{k-1} \left[1 - \left(\frac{v_D}{v_1} \right)^{k-1} \right] = \frac{F}{k-1} \left[1 - \left(\frac{P_1}{P_D} \right)^{\frac{k-1}{k}} \right] \quad (2.92a)$$

Here, $T_D \cdot v_D$ and P_D are the temperature, specific volume and pressure independently of explosion. T_1 , v_1 , and P_1 are the temperature, specific volume and pressure independently in expansion process.

$F = nRT_D$ is the power of an explosive. n is the mole number of gas products from 1 kg explosive.

$R = P_0 V_0 / 273$, P_0 is the air pressure, V_0 is the standard volume of 1 mol gas. If the unit of P_0 is atm, V_0 is liter, the unit of F is (L atm)/kg.

When the expansion of explosion products is unlimited, $P_1 = P_0$, $T_1 = T_0$, $V_1 = V_0$.

$$A = A_{\max} = IQ_w \quad (2.92b)$$

Here, I is the heat work equivalent; $A_{\max} = IQ_w$ is the potential energy of an explosive.

Equation 2.92b assumes that all explosion products are gases. If the explosion products are not only gases, they have gases, solids, and liquids, $A_{\max} < IQ_w$. In the

calculation of theoretical $A_{\max}$, the heat transfer of gas–solid and gas–liquid should be taken into consideration.

For the explosion in free space, the separation of shock waves from detonation fronts sometimes occurs before the heat transfer of gas–condensed states. The energy transferred to shock waves is only part of the explosion heat/energy. When explosion occurs in the air, not all chemical reactions are complete because of the scattering of reactants, and the explosion heat/energy is not used completely and efficiently in work. Increasing the diameter of the packed explosive benefits the above reactions. When the radius r_0 of the packed explosive and the particles radius r are fixed, 70 % of chemical energy is transferred into shock waves.

Though the detonation pressure is not as high as brisant explosives, the reaction time of detonation is longer. Followed by the explosion products impacting the surrounding media and the formation of shock waves, the action time of positive pressure is much longer than the condensed explosives. This is the key feature of explosion from liquid explosives. Figure 2.30 is the explosion of 3,000 g liquid explosive.

(1) The damage of air shock waves for buildings

The damage ability and degree of air shock waves for buildings are related with the building's vibration periods, and the action time t_+ of positive pressure of air shock waves. Most experiments show that when $t_+/T \leq 0.25$, the impulse of air

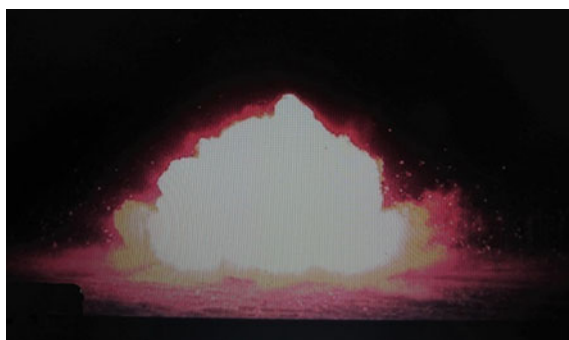


Fig. 2.30 Explosion of 3 kg liquid explosives



Fig. 2.31 Deconstruction/damage of *n*-butyl nitrate for brick structure buildings, **a** before explosion, **b** in explosion, **c** after explosion

shock waves plays the most important role for the damage of buildings. The writer designed an experiment of nitro *n*-butyl nitrate for buildings' damage.

Figure 2.31 indicates that the damage of *n*-butyl nitrate to brick structure building is very clear/obvious. When $t_+/T \geq 10$, the damage of air shock waves to building is determined by the super pressure of shock waves.

The positive pressure action time t_+ in the explosion of liquid explosive is very long. The boundary conditions of buildings to explosion center is a topic which is worth the study. According to energy conservation law:

$$R = \sqrt{\frac{BW}{\sigma h}} \cdot \sqrt{4 \frac{3E}{\rho}} \quad (2.93)$$

Here, R is the distance of one building to explosion center; E is the elastic modulus of building materials; σ is the stress of building materials; ρ is the density of building materials; B is a coefficient; and W is the mass of an explosive.

If the stress σ in Eq. 2.93 is replaced by allowance stress $[\sigma]$, the resulted R is the nearest distance with building not being damaged, or safe distance. If the stress is replaced by limit strength σB , the resulted R is the destruction range. Table 2.4 lists the limited strengths of common construction materials.

Table 2.4 σ_B , E , and volume-weight values γ of construction materials

Materials	E (kg/m ²)	σ_B (kg/m ²)	Volume-weight γ (kg/m ³)
Wood	10^9	3×10^6	600
Concrete	2×10^9	5×10^6	2,600
Steel	2×10^{10}	2×10^6	7,800

Table 2.5 k values of several objectives

Objectives	k	Damage degree
Plane	1	Complete damage of airplanes
Locomotive	4–6	
Ship	0.44	Damage of buildings on a ship
Nonarmored ship	0.375	Damage of ships ($W < 400$ kg)
Assembly glass	7–9	Broken into pieces
Wood siding wall	0.7	Damage ($W > 250$ kg)
Anil wall	0.4	Breaches ($R = k\sqrt{\frac{W}{h}}$, h is the thickness of wall with unit m, $W > 250$ kg)
Anil wall	0.6	Cracks
Nonfirm wood–stone buildings	2.0	Damage
Concrete all	0.25	Severe damage

Table 2.6 Anti-air-shock wave ability of buildings

Pressure of air shock waves ΔP (MPa)	Damage of buildings
<0.002	Little damage of buildings, few cracks on the window glass, seldom window shaking out
0.002–0.012	Little mild damage, part or large part of window glass broken
0.012–0.030	Mild damage, all glass broken, part doors and windows broken, cracks (<0.5 mm) and tilt of brick walls, building top shaking out
0.030–0.050	Medium damage, cracks (0.5–5 mm) and tilt (10–100) of brick walls, cracks of concrete walls, building top shaking out, most part damage
0.050–0.076	Severe damage, windows and doors destroyed, cracks (>50 mm) and high tilt of brick walls, partial falling down, severe cracks of concrete walls, falling down of brick buildings
>0.076	Falling down of brick walls and concrete buildings

After all constants are merged, Eq. 2.93 is simplified as 2.94.

$$R = k\sqrt{W} \quad (2.94)$$

The coefficient k is related with targeted staff. Some are found in Table 2.5

According to the experiments and experience from scientists of all over the world, the anti-air-shock wave ability of buildings is concluded in Table 2.6.

(2) Damage of air shock waves for human

Liquid explosives have very strong shock waves, especially the resonant waves produced in the group explosion. The writer used 200 kg XJ-1 explosive, and separated them into 66 bottles/cans with 3,000 g each. These 66 bottles are placed on 900 mm × 900 mm square ground with two layers. The explosion effect is in Fig. 2.32.

The super pressure data of group explosion are listed in Table 2.7.

The data in Table 2.7 indicate that the explosion super pressure of XJ-1 liquid explosive reaches 1.063 MPa at 20 m away from explosion center. It is imaginable

Fig. 2.32 Explosion of XJ-1 explosive (200 kg)



Table 2.7 The super pressures of shock waves from 200 kg XJ-1 explosives

Distance (m)	20	25	30	35	40	45	50
Pressure (MPa)	1.063	0.916	0.515	0.392	0.0892	0.0423	0.0187
Distance (m)	55		60	65	70	75	80
Super pressure (MPa)	0.0102		0.0137	0.0106	0.0096	0.0091	0.0062

that the super pressure of shock waves is very high in the explosion of liquid explosive.

The writer tried a lot of experiments of shock waves. The animals in experiments were a breed, which is close to human. All experiment conditions and results are below.

XJ-1 liquid explosive of 80 kg was used in the explosion. The animals were put into places, which were different away from explosion center with different super pressures. The damage of animals is listed in Table 2.8. The classic shock wave curve of 30 m away from explosion center is schematic in Fig. 2.33.

Table 2.8 shows that when the super pressure is 0.152–0.164 MPa, there is not any injury for 6 animals; while when the super pressure is 0.166–0.20 MPa, there is only one animal which is mild injured, and it dies of myocardial necrosis. So 1.66 MPa is the bottom super pressure value which can cause injury for animals. Following the peak value increase of super pressure, the injuries are heavier, and the incidence is higher. When the super pressure is lower than 0.2 MPa, the incidence rate is only 8 % (only one injured among the 12 animals), and the degree is mild. When the super pressure is 0.2–0.45 MPa, the incidence rate increases notably and reaches 71 % (10/14). When the super pressure is larger than 0.529 MPa, all animals are injured with 100 % incidence. And there are also medium and severe injuries.

If there are some protective facilities in experiment, the shock waves first break the protective facilities, then impact crafts. This prolongs the time of pressure increase, and the pressure increase of shock wave curve need longer time. The anti-impact ability of animals improves notably. Severe injuries or death occurs at 0.60 MPa.

The special experiments with shortening pressure increase time and prolonging the impact time of positive pressure are designed. All results are in Table 2.9.

The data of Table 2.9 indicates that decreasing the booster time with similar super pressure peaks obviously increased the shock injury degrees of animals. So for the places/position without protection, the shock waves significantly increase the shock injury for staff. The injury degrees of shock waves for staff are listed in Table 2.10.

Table 2.8 Injury statistics of animals from the different super pressure of air shock waves

Group number	Parameters of shock waves		(1)	(2)	Injury								Injury degree										
	ΔP (kg/cm ²)	t_f (ms)			(3)	(5)	(6)	(7)	(8)	(4)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)	(19)	(20)	(21)
I	1.52–1.64	200–237	1,040–1,100	6	0																		6
I	1.66–2.00	202–218	1,040–1,140	6	1				1													1	5
I	2.25–4.09	162–218	1,040–1,380	10	7	5			2				3	1								7	3
I	4.09–4.79	138–169	1,380–1,800	4	3	2			1				1	2	1		1					3	1
I	5.29–5.87	137–140	1,324–1,900	6	6	1	1	2	3				3	4	1		1				2	1	3
I	6.00–6.38	142–154	1,960–2,320	3	3	1	1	1	1				1	3				3	3	1	1	1	
Total				35	20	9	2	3	8	1			8	10	2	1	4	4	1	3	2	15	15

Note (1) Number of animals in experiment; (2) number of being injured; (3) myocardial bleeding; (4) myocardial necrosis; (5) mild; (6) medium; (7) severe; (8) mild; (9) medium; (10) emphyxis; (11) ruptured ear drum; (12) bleeding of other organs; (13) bladder; (14) spleen; (15) stomach; (16) epinephros; (17) spleen; (18) brain; (19) severe; (20) medium; (21) mild; (22) no

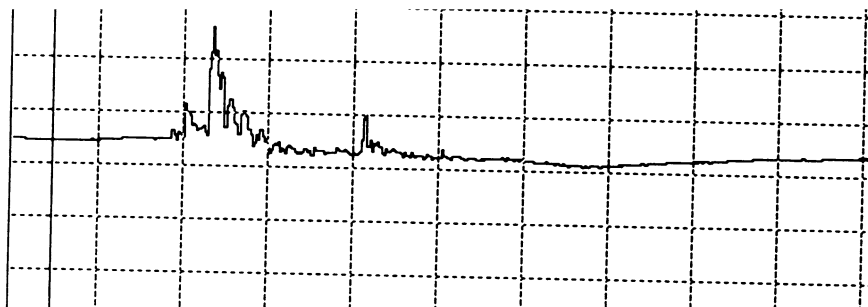


Fig. 2.33 Classic shock wave curve of 30 m away from explosion center

2.4.2 Explosion of Liquid Explosives on the Ground

The application of liquid explosives refers the explosion in rocks and earth. The stratum (including rocks and soil) is a kind of nonuniform media. There are large gaps between rocks and rocks, rocks and the soil, soil and soil. Even in the same rocks, there are big differences in the textures, structures, or mechanical properties. Study of explosion in the rocks is more complex compared to that in the air or under water. To study the impact of liquid explosives in the mining, explosions in infinite rocks and infinite half rocks are discussed here.

2.4.2.1 Explosion Characteristics Inside Rocks and Soil

Physical phenomena of explosion in infinite rocks. Figure 2.34 represents the explosion cross section of spherical or cylindrical explosives. After ignition, detonation waves spread at the same speeds. The transportation velocities depend on the species of explosives. The transportation of liquid explosive waves is faster than that of stress waves in the rocks. The deformation of rocks and soil is much slower. So in the explosion, the surrounding media is approximately impacted directly from explosion products. And the impacts from detonation positions and detonation waveforms are negligible. So the explosion in the rocks is a classical spherical detonation. The explosion induces the fast deformation process. There is no heat exchange between the surrounding media and detonation productive gases. This explosion is an adiabatic process.

After detonation, the pressure of explosion product gases reaches several ten kilo atmospheres. Under the impact of high-temperature and high-pressure explosion product gases, the surrounding rocks are severely compressed. Their structures are damaged, and particles are crushed, even are liquefied suddenly. The whole rocks move radially, and exclusion zone or empty zone are formed. Outside the zone, deformation slip surfaces are induced. Inside the zone, structure damage and crush

Table 2.9 Injuries of animals by shortening pressure increase time (t_I) and prolonging the impact time (t_+) of positive pressure

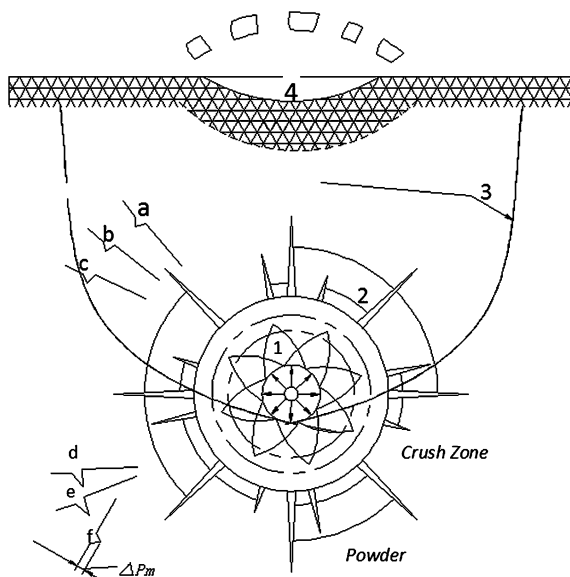
Group number	Parameters of shock waves			(1)	(2)	Injury					Injury					Injury degree											
	ΔP (kg/cm ²)	t_I (ms)	t_+ (ms)			(3)					(4)					(11)	(12)	(13)			(17)	(18)	(19)	(20)	(21)	(22)	
						(5)	(6)	(7)	(8)	(9)	(10)	(14)	(15)	(16)													
III	6.43–6.56	51		4	4			2		2		2	4				2	1	3	2	2						
	6.07–6.15	177–188		3 ^a	3			2	1	1	2		1	3						2	1	2					
I	6.0–6.38	142–154		3 ^a	3	1	1	1	1	1											1	1	1				

^a Means death in the explosion. One animal is not in the statistics because it was dead in the explosion

Table 2.10 The injury degrees of shockwaves for staff

Super pressure of shockwaves (with-out booster) (kg/cm^2)	Injury degrees
0.02–0.03	Slight (slight contusion)
0.03–0.05	Medium (hearing injury, medium contusion, mild bleeding of organs, fractures)
0.05–0.10	Severe (severe contusion of organs, may cause death)
>1.0	Extremely severe (may cause death in large extent)

Fig. 2.34 Explosion of liquid explosives inside the rocks and soil. 1 Crush zone; 2 crack zone; 3 permanent and elastic deformation zone; 4 top free soil subsidence because of reflective waves. *a, b, c* the sequence change of pressure waves in the dry soil; *d, e, f* the sequence change of pressure waves in the rocks



of rocks result in fine cracks with compression. In this zone, the shock waves transport with super sonic velocity.

Following the shock wave fronts travel far away from explosion center, the energy distributes the space, which is linearly proportional to the cubic of distances. So the pressure of shock waves decreases rapidly. At certain distance, the super pressure is lower than the limit strength of rocks, and the deformation changes with crushing and slip surface disappearing, the structure of rocks and soil kept. Under the compression of shock waves, the rocks and soil move out radially. Each cycle unit is under drawing stress. When this drawing stress is larger than the limit tensile strength of rocks and soil, the radial cracks from explosion center to out are produced. This zone is destruction zone, which is much larger than above two zones.

Because of inertia, after the explosion shock waves leave the explosion zone, the earth continues to leave from the explosive places and lasts some time. It induces the negative pressure of explosion zone, and the transportation of sparse waves.

The shock waves are very weak outside of the crack zone. These shock waves could not induce the deconstruction of rocks and soil, but only the vibration of particles. And the amplitude of vibration are smaller if the particles are further from explosion center, finally it decays into sound waves. For brittle soils, explosion zone is surrounded by compressive zone, crack zone, and vibration/oscillation zone. For cohesive soils, the compressive zone is the closest to explosion zone. The sizes of different zones are related with the properties of explosives, the explosive mass, the packing structure, and the soil properties.

2.4.2.2 Explosion of Liquid Explosives in Infinite Half Rocks and Soils

In engineering blasting, explosion occurs under ground with certain depth. The earth surface greatly impacts the explosion effects. Figure 2.35 gives the explosion in the earth of rock–soil free surfaces. In the first stage of explosion, the explosion waves transport to all directions from the explosion center.

When the explosion pressure waves reach the free interface of soils and air, they transport down from the free interface (Fig. 2.35b). Because of expansion waves and the pressure of product gases, the top soils above the explosives lift up (Fig. 2.35c). The tensile waves and shear waves are produced. These second stage producing waves transport radially to all directions have the maximum amplitudes, and induce the waves with maximum oscillations on the earth surface.

The transportation of earthquake waves is faster in rocks than in soils. In blasting engineering, there are loose blasting and throwing blasting.

(1) Loose blasting [21]

In loose blasting, explosives are deeper than throwing blasting. The explosion waves loose the surrounding rocks and soils, but they do not throw rocks and soils. After explosion, the explosion waves transport in all directions. When explosion

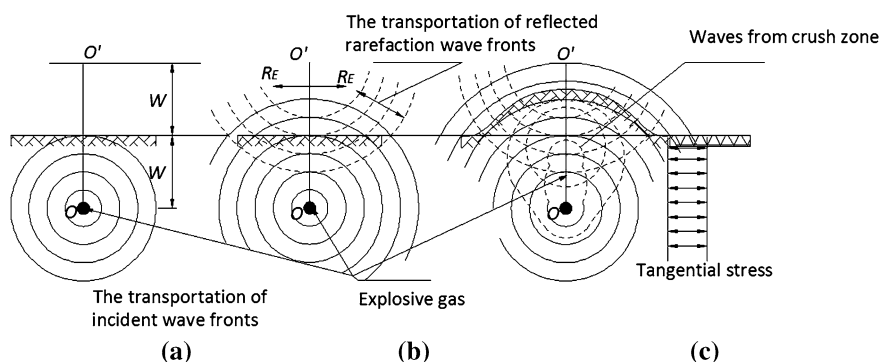


Fig. 2.35 The three stages of explosion in the surface media [21]. **a** the transportation of pressure waves; **b** radiation of pressure waves from free surface and the formation of sparse; **c** uplifting of soils

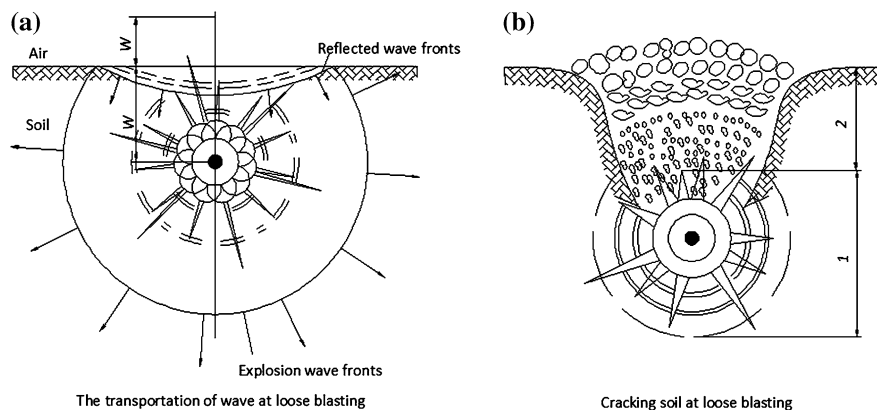


Fig. 2.36 Phenomena of loose blasting [21]. 1 inside cracking zone; 2 out cracking zone

waves pass through, the particles of media move out radially, and stop by the outer layer media. But if there are ground surfaces or other free surfaces, the rocks and soils of the free surfaces are not stopped by the outer layer media, and move out radially. At the same time, the explosion waves become tensile waves from free surfaces with transportation velocity of sound (Fig. 2.36a).

Wherever the radiant waves reach, the rocks and soils are under drawing extension. If the drawing tension is larger than the limit of ultimate tensile strength, the free surfaces expand inside layer by layer. Reflected extension waves are approximately spherical waves from optical mirror virtual center O' of explosives.

The damage of loose boosting has two parts.

- (1) Part 1 is inside cracking zone (Fig. 2.36b), which is a spherical zone with radial cracks, and with fine medium particles.
- (2) Part 2 is out cracking zone, which is produced by the damage of tensile waves from free surfaces. The key feature of this zone is that the cracks expand along the spheres of virtual centers with relatively larger medium particles. The shape of this zone looks like a funnel. So this zone is also named as loose funnel.

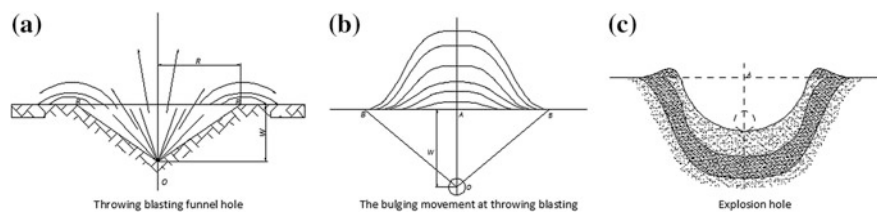


Fig. 2.37 Three different phenomena in the throwing blasting [21]. **a** A throwing blasting cone, **b** the bulging motion in a throwing blasting, **c** an explosion cone

The existence of free surface increases the damage. In engineering explosion, increasing the free surfaces is used to improve the efficiency of explosion.

(2) Throwing blasting [21]

When the packing mass of an explosive is increased and the explosive is closer to the ground, once the energy of explosion is larger than the resistance of the media above the explosive, the crushed rocks and soils are thrown upward in the shape of a speaker. At the same time, a throwing blasting cone is generated, which is from the explosion center to the ground (Fig. 2.37).

In Fig. 2.37, the vertical distance from the explosive center to the free surface is the smallest resistant line, which is represented by W^* . The radius of the blasting cone is R .

Figure 2.37 also indicates that the throwing blasting is a process of rock and soil transportation. After a single explosion or detonation, the position OA, which is the smallest resistant line, protrudes first, and the protrusion extends to the surrounding. The lifted height and extending range increase following that time prolongs. Though the height lifting continues, the range extension stops once it reaches a certain range. This process is the bulging motion stage. The bulging breaking and scattering stage is that the crushed rocks and soils move upward as an entirety, when the lifted height reaches 1–2 times of the smallest resistant line, the top bulging breaks, then the explosion products and rock and soil fragmentations scatter upward together. The rock and soil fragmentations fly in air, and finally fall on the ground under the impact of gravity. Part of fragmentations fall into the cone, and part fall on the ground near the cone. Compared to the protrusion of the ground, this cone is named “rim” (Fig. 2.37c). In the above stages of a single blasting explosion, the bulging motion of rocks and soils has the maximum linear speed in the direction of the smallest resistant line OA. The linear speed is smaller when it is farther away from OA. And the speed of point B (the edge of the cone) is the smallest, zero.

When the rocks and soils are just thrown up, the sparse waves transport into them because of the relatively lower surrounding pressure. At the same time, the sparse waves crush the rocks and soils further. According to the throwing index n , there are several explosion/detonation conditions, which are listed below.

- (1) $n > 1$ is the strong blowing blasting. The vertex of crater pit is larger than 90°
($n = \frac{R}{W^*}$)
- (2) $n = 1$ is the standard blowing blasting. The vertex of crater pit is 90°
- (3) $0.75 < n < 1$ is the weekend blowing blasting. The vertex of crater pit is smaller than 90°
- (4) $n < 0.75$ is the loose blasting. There are no rocks and soils to blow.

2.4.3 Explosion of Liquid Explosives in Semienclosed Space [22, 24–26]

The explosion of liquid explosives releases more gases. The super pressure of explosion on the ground within 0.5–1.0 m is lower than condensed explosives. But the detonation positive pressure impacts longer time than condensed explosive, especially the places, which are far from the explosion center, for example, the zone outside of explosion reactions. The explosions of liquid explosives are more powerful in semienclosed space, especially in semiunderground or underground.

2.4.3.1 Reflection of Shock Waves from Rigid Barriers

When the air shock waves of explosion from liquid explosive meet the vertical rigid wall (barrier), the velocity of air mass points drops down to zero suddenly, which accumulates the mass point, and the pressure and density increase dramatically until certain degrees. Then the mass points reflect to the opposite direction, the reverse shock waves are produced. Semienclosed space is different from free space. The superposition of reverse waves rises the pressure to an extremely high level.

(1) Explosion from the reflection of shock waves

Figure 2.38 gives the reflection of shock waves when they meet the vertical rigid unlimited walls. If the incident waves are one-dimensional steady ones, the reflection waves are also one-dimensional steady waves. The parameters of air are P_0 , T_0 , ρ_0 , $v_0 = 0$ before being bothered and the parameters of incident wave fronts are, P_0 , ρ_1 , T_1 , and v_1 . Because the wall is absolutely rigid, the air particles close to the wall are in a stationary state before reflection. When shock waves meet the rigid wall, the air particles near the wall produce the reflection waves with velocity/speed D_2 . The direction of reflection waves is the opposite of incident waves. The parameters of reflection wave fronts are P_2 , T_2 , ρ_2 and $v_1 = 0$ because of the rigidity of the wall.

From the basic functions of shock waves, below equations are obtained.

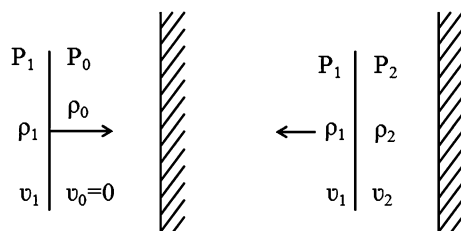


Fig. 2.38 The reflection of shock waves in semienclosed space when liquid explosives explode

$$\vartheta_1 - \vartheta_0 = \sqrt{(P_1 - P_0) \left(\frac{1}{\rho_0} - \frac{1}{\rho_1} \right)}$$

$$\vartheta_2 - \vartheta_1 = -\sqrt{(P_2 - P_1) \left(\frac{1}{\rho_1} - \frac{1}{\rho_2} \right)}$$

Because the direction of reflection waves are opposite from the incident ones, the incident waves are positive, the reflection waves are negative, and $\vartheta_1 = \vartheta_2 = 0$, so

$$(P_1 - P_0) \left(\frac{1}{\rho_0} - \frac{1}{\rho_1} \right) = (P_2 - P_1) \left(\frac{1}{\rho_1} - \frac{1}{\rho_2} \right)$$

or

$$\frac{P_1 - P_0}{\rho_0} \left(1 - \frac{\rho_0}{\rho_1} \right) = (P_2 - P_1) \left(1 - \frac{\rho_1}{\rho_2} \right) \quad (2.95)$$

The adiabatic function of shock waves is below.

$$\frac{\rho_1}{\rho_0} = \frac{\frac{k+1}{k-1} \cdot \frac{P_1}{P_0} + 1}{\frac{k+1}{k-1} + \frac{P_1}{P_0}}, \quad \frac{\rho_2}{\rho_1} = \frac{\frac{k+1}{k-1} \cdot \frac{P_2}{P_1} + 1}{\frac{k+1}{k-1} + \frac{P_2}{P_1}}$$

Substitute the adiabatic function into Eq. 2.95

$$\begin{aligned} & \frac{2(P_1 - P_0)^2}{\rho_1[(k-1)P_1 + (k+1)P_0]} \\ &= \frac{2(P_2 - P_1)^2}{\rho_1[(k+1)P_2 + (k-1)P_1]} \\ &= \vartheta_1^2 \end{aligned}$$

The super pressure of incident waves is $\Delta P_1 = P_1 - P_0$

And the super pressure of reflection waves is $\Delta P_2 = P_2 - P_0$

The above equation is changed to

$$\frac{\Delta P^2}{(k-1)\Delta P_1 + 2kP_0} = \frac{(\Delta P_2 - \Delta P_1)^2}{(k+1)\Delta P_2 + (k+1)P_2 + (k-1)\Delta P_1 + 2kP_0}$$

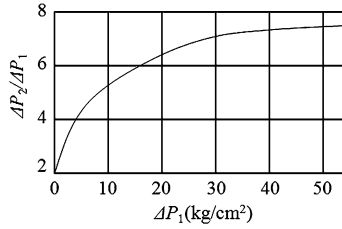


Fig. 2.39 The pressure relationship of reflection waves and incident shock waves [21]

The peak super pressure of reflection waves is Eq. 2.96.

$$\Delta P_2 = 2\Delta P_1 + \frac{(k+1)\Delta P_1^2}{(k-1)\Delta P_1 + 2kP_0} \quad (2.96)$$

For air, $k = 1.4$. Substitute it into 2.96, the super pressure of shock waves is 2.97.

$$\Delta P_2 = 2\Delta P_1 + \frac{6\Delta P_1^2}{\Delta P_1 + 7P_0} \quad (2.97)$$

For strong shock waves,

$$P_1 \gg P_0$$

so

$$\frac{\Delta P_2}{\Delta P_1} \approx 8$$

For weak shock waves, $P_1 - P_0 \leq P_0$ so

$$\Delta P_2 / \Delta P_1 \approx 2$$

The above conditions conclude that in semiclosed space, the pressure of reflection wave is 2–8 times of the pressure from incident shock waves. It is listed in Fig. 2.39.

One thing is worth noticing that under strong shock waves, the pressure of reflection waves is 8 times of that from incident, which is not always correct. The strong shock waves are high-temperature and high-pressure, and perfect gas is different from the real air. Döering, Burkhardt, Shear, and Mecane referred that if the dissociation and ionization of gases are in consideration, $\Delta P_2 / \Delta P_1$ is much larger than eight, and it reaches twenty or even more.

The transportation velocity of reflection shock waves D_2 is Eq. 2.98.

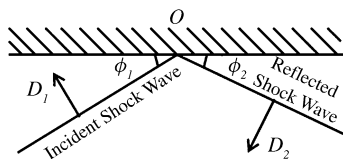


Fig. 2.40 The oblique reflection of shock waves on rigid surfaces/walls [21]

$$D_2 = \sqrt{\frac{2}{\rho_0(k-1)P_1 + (k-1)P_0}} \times [(k-1)P_1 + P_0] \quad (2.98)$$

The density of reflection shock wave fronts is Eq. 2.99.

$$\frac{\rho_2}{\rho_1} = \frac{kP_1}{(k-1)P_1 + P_0} \quad (2.99)$$

The above equations apply when $\frac{P_1}{P_0} < 40$. Otherwise, the ionization of air must be considered.

(2) Oblique reflection of air shock waves

The oblique reflection of shock waves occurs when the incident air shock waves have an angle ϕ_1 with the surface of a barrier. The angle ϕ_2 between the reflected waves and the surface of barrier may not be equal to ϕ_1 . D_1 and D_2 are the transportation velocities of incident waves and reflected waves. Because of reflection, the velocity component vertical to the surface equals zero (Fig. 2.40).

In Fig. 2.40, point O moves toward the right with rate $\frac{D_1}{\sin \phi_1}$ on the barrier surface. Moving coordinates with rate $\frac{D_1}{\sin \phi_1}$ to the left are used for study and recognition of oblique reflection. Thus, the incident shock waves and reflection shock waves are immobile wave fronts; while the still air moves toward the right with rate $q_0 = \frac{D_1}{\sin \phi_1}$ (Fig. 2.41).

In Fig. 2.41, “O” represents the zone of not being bothered; “I” refers the zone in with incident shock waves passing through and reflected shock waves not reaching;

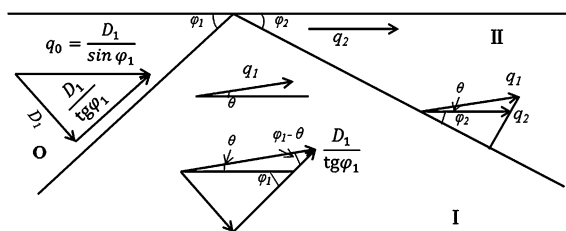


Fig. 2.41 Reflection moving coordinate of shock waves on the rigid surface [21]

“II” means the zone with reflected shock waves passing through. q_1 and q_2 are flow rates of air in “I” and “II” zones separately.

After passing the shock wave fronts, both the velocity/rate and direction of air change. The tangential component parallel to shock wave fronts remains constant, and the normal component becomes smaller. So the direction of flow turns toward the wall/surface. Below equation is obtained from Fig. 2.41.

$$q_0 \cos \varphi_1 = q_1 \cos(\varphi_1 - \theta)$$

In the two sides of incident wave fronts, both energy and momentum are conserved.

$$\rho_0 q_0 \sin \varphi_1 = \rho_1 q_1 \sin(\varphi_1 - \theta)$$

$$P_0 + \rho_0 q_0^2 \sin^2 \varphi_0 = \rho_1 q_1^2 \sin^2(\varphi_1 - \theta) + P_1$$

Likewise, the incident flow in “I” zone is q_1 . It inflows “II” zone with an angle of $\varphi_2 + \theta$ from the fronts OR of reflected waves. Because of the impact of velocity component $q_1 \cos(\varphi_2 + \theta)$, the reflected flow q_2 directs outward and it is parallel with the rigid surface. For the two sides of reflected waves, below equations are established.

$$q_2 \cos \varphi_2 = q_1 \cos(\varphi_2 + \theta)$$

$$\rho_2 q_2 \sin \varphi_2 = \rho_1 q_1 \sin(\varphi_1 + \theta)$$

$$\rho_2 q_2^2 \sin^2 \varphi_2 + P_2 = \rho_1 q_1^2 \sin^2(\varphi_2 + \theta) + P_1$$

The impact adiabatic function of incident waves and reflected waves are

$$\frac{\rho_1}{\rho_0} = \frac{(k+1)P_1 + (k-1)P_0}{(k-1)P_1 + (k+1)P_0}$$

and

$$\frac{\rho_2}{\rho_1} = \frac{(k+1)P_2 + (k-1)P_1}{(k-1)P_2 + (k+1)P_1}$$

P_2 , ρ_2 , φ_2 , q_1 and θ are obtainable from above equations. The calculation process is very complex. As a matter of convenience, the oblique reflection is simplified to Eq. 2.100.

$$\Delta P_2 = (1 + \cos \varphi) \Delta P_1 + \frac{6 \Delta P_1^2}{\Delta P_1 + 7 P_0} \cos^2 \varphi_1 \quad (2.100)$$

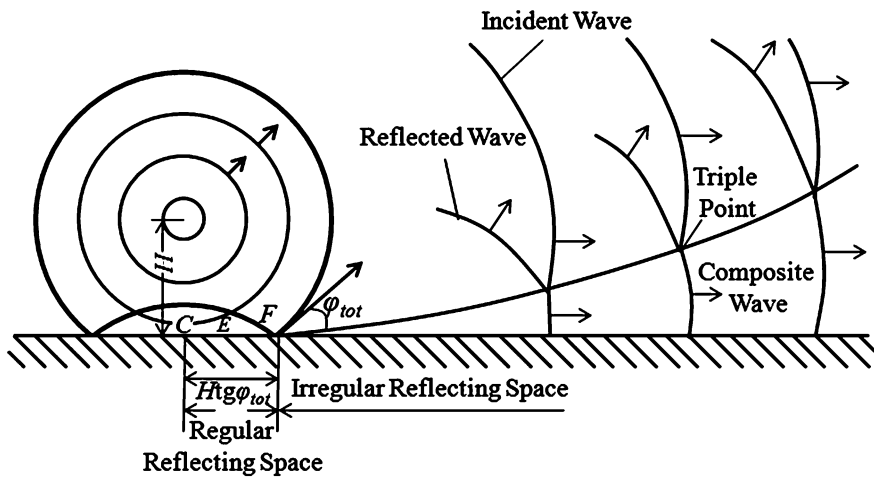


Fig. 2.42 Mach reflection

The properties of reflected waves are listed below.

- (1) For a given strength of incident waves, there is critical angle φ_{1c} , that when $\varphi_1 > \varphi_{1c}$, there is no reflection. For air with specific heat ratio $k = 1.4$, the limit of weak shock waves is $\varphi_{1c} = 90^\circ$; the limit of strong shock waves $\varphi_{1c} = \sin^{-1} \frac{1}{K} = 39.97^\circ \approx 40^\circ$.
- (2) For each gas, there is an angle

$$\varphi' = \frac{1}{2} \cos^{-1} \left(\frac{k-1}{2} \right)$$

When $\varphi_1 > \varphi'$, the intensity of reflected waves is larger than that of front reflection. For air, $\varphi' = 39.23^\circ$.

- (3) For a given strength of incident waves, there is an incident angle $\varphi_{\min}$. When $\varphi_1 = \varphi_{\min}$, the reflection intensity P_2/P_0 has the minimum value.
- (4) Reflection angle φ_2 is a monotonic increasing function of φ_1 .

(3) Mach reflection of shock waves [27, 28]

In the regular reflection, when incident angle φ_1 is larger than the critical angle φ_{1c} , the above reflection rule does not work. Ernst Mach indicated that the merge of incident and reflected shock waves produces the third shock waves—Mach waves. This phenomenon is Mach reflection.

The general explosion in air occurs in a limited height. The shock waves are in spherical shape. After transportation in air, the radius of the sphere becomes larger gradually, and exceeds the height H . Now part shock waves run into the ground. On the projected point of explosion center, the propagation direction of shock wave

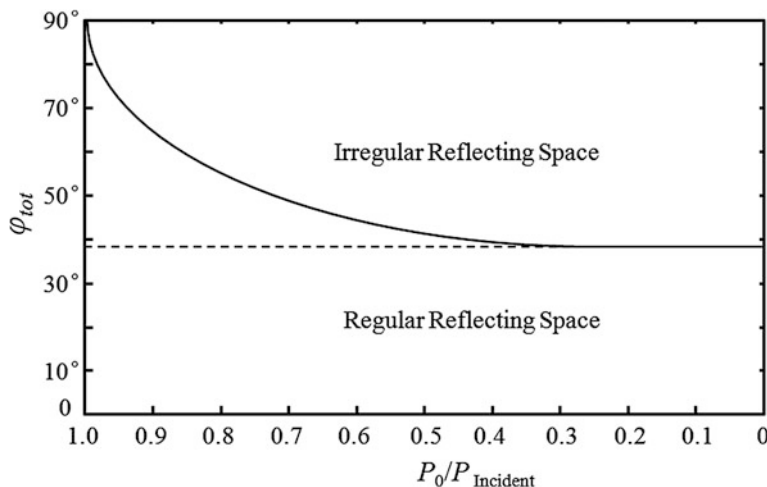


Fig. 2.43 The relationship of reflective critical angle and pressures

fronts is perpendicular with the ground surface (Fig. 2.42). This reflection is the front reflection.

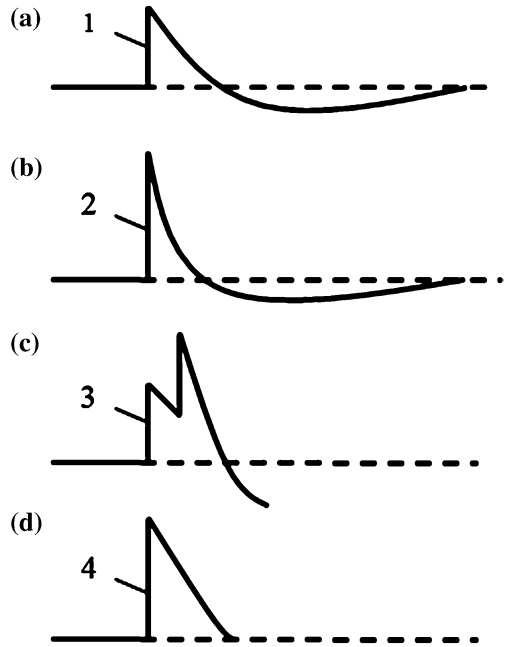
Following the shock wave fronts leave the projected point; the propagation of incident wave fronts has an angle φ_1 with the ground. Now it is the oblique reflection. Following the increase in distance of the shock wave fronts from the projected point, the incident angle φ_1 is larger and larger while the angle between incident shock wave fronts and reflected shock wave fronts. When $\varphi_1 \geq \varphi_{1c}$, the reflected wave fronts catch and attach incident waves to form another single shock waves—composite waves. This composite waves are Mach waves.

Because the attaching of incident waves to reflective waves proceeds gradually along height, the fronts of composite waves have bigger and bigger height following the distance increase to explosion center. In Fig. 2.42, the cross point of wave fronts from the incident, reflective, and composite waves, is triple point.

The whole space above ground is divided into two parts. (1) Regular reflective space, or close space of aerial burst. Its distance to projective point is shorter than $H \cdot \tan \varphi_{1c}$. All buildings and targets inside the space experience two shock waves: incident and reflective waves. (2) Irregular reflective space, or far space of aerial burst. Its distance to projective point is longer than $H \cdot \tan \varphi_{1c}$. All buildings and targets inside the space and below triple point only experience composite waves.

The propagation of air particles in the vertical direction is stagnated. So the propagation of air particles after fronts of reflective waves (including composite waves) is horizontal. It is zero in the front reflection. But the air particles before fronts of composite waves are still. After composite waves pass them, the air particles obtain propagation, which is horizontal with the ground. In theory, the front of composite waves, or Mach rod, is perpendicular with the ground.

Fig. 2.44 The classic shapes of waves. **a** Incident wave, **b** reflective wave, **c** wave of regular reflection **d** wave of Mach reflection



It should be pointed out that the critical angle of Mach reflection is related with the intensity of incident waves. It is shown in Fig. 2.43.

Figure 2.42 gives the reflective conditions of aerial explosion on point C, E, F, etc.

- (1) At point C, the incident waves are perpendicular with the ground (Fig. 2.44a). The reflection at point C is front reflection. The curve shape of reflection waves is curve 2 of Fig. 2.44b.
- (2) At points E and F, the front of incident waves has an angle φ_1 with the ground, and $\varphi_1 < \varphi_{1c}$. The reflection is oblique reflection. Its curve shape is curve 3 of Fig. 2.44c.
- (3) When $\varphi_1 > \varphi_{1c}$, Mach reflection produces. Its curve shape is curve 4 of Fig. 2.44d.

The above three conditions are concluded below.

- (1) when $\varphi_1 = 0$, front reflection and regular reflection

$$\Delta P_2 = 2\Delta P_1 + \frac{6\Delta P_1^2}{\Delta P_1 + 7P_0}$$

- (2) when $0 < \varphi_1 < \varphi_{1c}$, oblique reflection and regular reflection



Fig. 2.45 Explosion of liquid explosives in semiclosed space

$$\Delta P_2 = (1 + \cos \varphi) \Delta P_1 + \frac{6\Delta P_1^2}{\Delta P_1 + 7P_0} \cos^2 \varphi_1$$

(3) when $\varphi_{1c} < \varphi_1 < 90^\circ$, Mach reflection and irregular reflection

$$\Delta P_m = \Delta P_{fG}(1 + \cos \varphi_1)$$

Here, ΔP_m is the super pressure of Mach reflection; and ΔP_{fG} is the super pressure of ground explosion.

2.4.3.2 The Damage of Semiclosed Targets from Air Shock Waves

The shock waves of liquid explosive explosion propagate inside the semiclosed space, release energy produce pressure for the semiclosed space. The shock waves destroy and injure the surrounding targets at different degrees. The damage and destruction of targets under explosion shock waves are a very complex process. The disturbance/perturbation of shock waves induces high pressure, which destroys the vulnerable spots in the semiclosed space, e.g., windows, air chimneys, crafts, etc. The destructiveness is related not only with shock waves, but also with the shapes, intensity, and resilience of targets. The explosion of liquid explosives in semiclosed space is shown in Fig. 2.45.

In Fig. 2.45, 1,800 kg liquid explosives are exploding in 120 m³ semiclosed room constructed by concrete-steel. The super pressure of shock waves from the explosion reaches 1.83 MPa. The high pressure lashes and devastates the targets inside the building. At the same time, being affected by the reflection, the high-pressure shock waves disturb the targets inside the building. The tremendous pressure difference between in and out of the building destroys windows, doors, etc. and other vulnerable parts. Figure 2.45 indicates that the destruction of windows and doors from liquid explosives is thorough. The damage of soft targets inside the building is hardly avoidable.

2.4.4 Explosion Effect of Liquid Explosives Under Water

2.4.4.1 Physical Phenomena of Explosion Under Water

When the loaded explosives explode under/in the unlimited water, the pressure of high-temperature and high-pressure products is much higher than hydrostatic pressure of water. So when liquid explosives explode under/in water, both shock waves and bubble pulse phenomena are produced. In physical properties, air and water have both similarity and difference. The explosion of liquid explosives in water has not only similar physical phenomena with that in air, but also different ones. The main difference is in three aspects: (1) For the explosion with same amount of explosives, the pressure of shock waves in water is much bigger than that of air shock waves, (2) The impact time of shock waves in water is much shorter than that of air shock waves, and (3) The propagation rate of air shock wave fronts is faster than that of front sound; while the propagation rate of shock waves in water is approximately front sound rate. The main reason for the difference is that water is noncompressible. Experiments indicate that volume change of water is $1/320$ from 7.5 to 10.0 MPa. The density change of water is $\Delta\rho/\rho \approx 0.05$ at 100 MPa. But under extremely high pressure, water is compressible. So water shock waves are produced under the high pressure of explosion products. The density of water is much larger than air. The hydrostatic pressure is different if the explosion is in different depth. The expansion of products in water is much slower than in air. The sound rate in seawater with 18 °C is about 1,494 m/s, higher than that in air. The sound rate in water changes if the gas amount in the water is different. When the air occupancy is 0.1–1 %, the sound rate in water drops to 900 m/s. While when the air occupies 6 %, the sound rate in water decreased to 500 m/s. From here we see that the explosion of liquid explosives under/in water is much complex than in air.

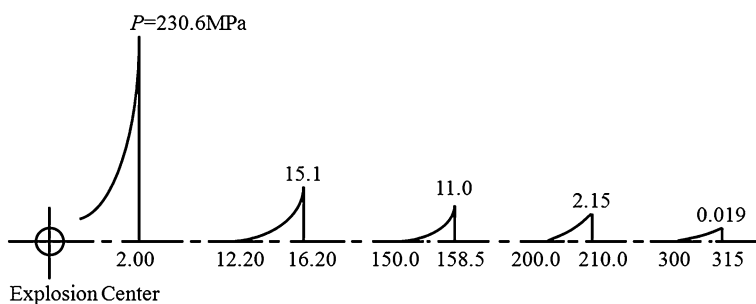


Fig. 2.46 Propagation of shock waves in water

2.4.4.2 The Explosion Shock Waves of Liquid Explosives Under Water

When the packed explosives explode in unlimited, uniform, and static water, the rapid expansion of explosion products first induces the formation of shock waves, which is followed by the generation of sparse waves by explosion products on the intersurface of products and water. The sparse waves propagate to the center of products, which is the reverse of shock waves. The pressure of original shock waves in water is much larger than that in air. For example, when the pressure of original shock waves in air is 80–130 MPa, the pressure of original shock waves in water is larger than 10,000 MPa. In the propagation of shock waves in water, both pressure of wave fronts and velocity/rate drops down faster. And the waves are broadened continuously. For the shock waves from explosion of spherical liquid explosives, their pressure decreases rapidly within $1\text{--}1.5 \gamma_0$. The pressure is only 1/100 of the original one. Figure 2.46 gives the measured shock wave pressure changes within different distances from the explosion of 100 kg hydrazine nitrate liquid explosives.

Figure 2.46 shows that the pressure drops faster when it is close to the explosion center; while the pressure drop slows down once it is far from the explosion center. In addition, in the explosion of liquid explosives under/in water, the positive impact time of shock waves is longer following the distance increasing, but it is much shorter than that of air shock waves. The impact time in water is only about 1/100 of that in air because the speed difference between fronts and tails is smaller in water. For example, when the pressure of water shock waves is $P = 500$ MPa, the velocity/rate of water shock waves is 2,040 m/s (when the pressure of water shock waves is 5 MPa (1/100 of water), the velocity of air shock waves is 2,230 m/s). When the pressure drops down to 25 MPa, the propagation velocity of water shock waves is close to sound rate (about 1,450–1,500 m). Now the fronts and waves have similar propagation rate.

The above-discussed shock waves are in unlimited water medium. The real water medium has free surface (intersurface of water–air) and water bottom. After the explosion of liquid explosives, the shock waves in water reach the free surface or water bottom, and then reflection is generated.

(1) Existence of free surface

When the water shock waves reach the free surface, there is a dark gray hydrosphere expanding rapidly on water surface. Its migration velocity is very large. This hydrosphere disappears several milliseconds later. The reflection of shock waves occurs on the free surface. According to the condition that the pressure is close to zero after the incident and reflective waves converge together, the reflective waves are sparse waves. (Because the acoustic impedance of water is much larger than that of air, according to the propagation theory of stress waves in different media, the reflective waves are sparse waves) Under the effect of sparse waves, the water particles/drops are splashed further up, and a special splashed water mizutsuka is generated. Later, the water bubbles of gas products arrive on the water surface, and a splashed water column is formed. The gas bubbles reach the water surface before they start contracting. Because the gas bubbles float slowly,

Fig. 2.47 Explosion of liquid explosives in/under water



they scatter radially. So the water column projects out of water radially. The gas bubbles have maximum compression when they reach the surface. And the floatation velocity of gas bubbles is much faster. Now all water above gas bubbles are projected upward, and a high and narrow fountain column is generated. The height and projection velocity of fountain columns are determined by the depth of explosives. The explosion phenomena of liquid explosives are in Fig. 2.47.

Because of the reflection of sparse waves from free surface, the damage of explosion in water is obviously improved compared to that on ground. This property can be used to improve the utilization rate of explosives. But if the explosion occurs in deep enough water, the bubbles are dispersed or dissolved before they reach the free surface. Now there is no fountain. For general explosives, the depth is calculated by below equation.

$$h \geq 9.0\sqrt{[3]W}$$

Here, h is the depth of explosives in water; and W is the mass of explosives

(2) Existence of water bottom

Like the explosion on the ground, explosion in water increases the pressure of water shock waves. For rigid water bottom, it equals two times of explosion power. In fact, the water bottom is not absolutely rigid, and it absorbs part of energy. Experiments indicate that in the water bottom with sandy soils, shock wave pressure increases up 16 % and impulse goes up 35 %.

In summary, the explosion of explosives in/under water generates water shock waves, bubble impulse, and pressure waves. All of these can cause serious damage for the targets.

2.5 Toxic Gas Production of Liquid Explosives in Explosion

2.5.1 Toxicity of Liquid Explosives

In the past more than 100 years, the application of explosives reached the extreme, in both amount and variety. Before the potential impact of explosives for environment was understood, the explosives and raw materials had already been discarded everywhere, and it caused the serious pollution of water and earth. The pollution makes people's health in potential remedies. And the direct discharge of explosion products endangered the environment and human health in some degree. Liquid explosives have a problem to poisonousness and pollution. The hazards of liquid explosives include two parts: the damage of explosion products and danger of explosive remnants to the environment and human. The two parts have their own hazardous substances and damage mechanisms separately. The detonation of liquid explosives generates complex explosion products, which endanger the environment and human. The complexity of liquid explosives in detonation makes the damage unpredictable and difficult to assess. The damages for environment and human are potential risks, which have not gained enough attention. If the liquid explosives are discharged into water, their components (such as nitric acid, hydrazine nitrate, nitrate ether, alkyl nitrate, aromatic nitro compounds, etc.) cause the water pollution in high levels. Mutagenicity of human organs is one of the invisible damages of liquid explosives

Take the pollution and damage of aromatic nitro compounds as an example. Impressive amount of poisonous aromatic nitro compounds are discharged into the environment each year, which destroys the ecological balance of nature and threatens human life directly or indirectly. According to reports, the danger of aromatic nitro compounds from military bases or disused plants of explosive production has impacted a large crowd and initiated the study boom of bioremediation. In general, nitro aromatic hydrocarbons coexist and impact with each other, which brings joint toxicity. The synergistic effect of joint toxicity increases the damage ability. All extra study concludes that nitro group plays an important role for being toxic and the *in vivo* reduction of nitro group is the main poisonous reaction. But further study continues now to make sure the toxicity from single electron reduction of nitro group, reaction of free radicals or other toxic reactions.

2.5.2 Toxicity from Explosions of Liquid Explosives

Liquid explosives are compounds, which have different oxygen, nitrogen, and carbon atom ratios. The detonation products have complex chemical ingredients, inorganic materials and organic products. Sample collection and data analysis of explosion products are different from that of air. The specific composition analysis

Table 2.11 Hazard concentration of toxic gases in air (mg L^{-1})

Toxic gas	Mild poisoning after several hours	Severe poisoning after 1 h	Lethal after 0.5–1 h	Dying after several minutes
CO	0.1–0.2	1.5–1.6	1.6–2.3	5
NO _x	0.07–0.2	0.2–0.4	0.4–1.0	1.5
H ₂ S	0.01–0.2	0.25–0.4	0.5–1.0	12
SO ₂	0.025	0.06–0.26	1.0–1.05	

is still a challenge for all scientists. From the mechanisms, the ideal detonation reactions only produce CO₂ and N₂, which are oxidized by oxygen from carbon and reduced from nitrogen oxides. However, the real detonation reactions are not ideal redox reactions. In the initial stage of explosion, the reactions are not complete, and the gas products deviate from expected results. In the detonation products, there are a lot of toxic gases, mainly carbon monoxide and nitrogen oxides (which include N₂O, NO, N₂O₃, NO₂/N₂O₄, and N₂O₅). All of these gases extremely endanger the health of human. For example, breathing in CO reduces the ability of blood transporting oxygen, which leads to severe hypoxia of tissue cells. 0.03 % of CO concentration in air is not safe. 0.15 % CO will causes suffocation poisoning or even death. The toxicity of NO₂ is larger than CO. NO₂ with lower concentration has long-term potential dangers. The toxicity of NO₂ mainly impacts the lungs. After being breathed in, NO₂ reacts with the moisture in the lungs to produce nitric acid and nitrous acid, which severely irritate and corrode the lungs tissues until edema. The toxicity of NO₂ is 6.5 larger than that of CO. If there is not enough oxygen, or the explosion conditions are not good enough, the products may have C_mH_n, NH₃, and HCN toxic gases, etc.; explosives with sulfur may produce SO₂ and H₂S. The toxicity of explosion products are mainly from the below two components.

(1) Interaction of explosion products and the surrounding media

Some rocks can react with detonation products, and also act as the catalysts of second reactions. For example, coal can reduce the CO and CO₂ of products. Iron oxide ore acts as the catalyst of CO oxidization to CO₂. Sulfide ore reacts with detonation products to produce sulfur oxide and hydrogen sulfide.

In addition, blasting operation, charge/packing density, charge/packing length, and stemming blockage of explosion holes impacted the formation of toxic gases to a certain extent. For industry explosives in blasting, ratio of mixtures, selection of oxygen balance, processing of explosives, and blasting operation should be taken into consideration. The hazard concentrations of toxic gases are in Table 2.11.

(2) Incompleteness of explosion reaction

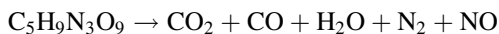
In the preliminary stage of explosion, the incomplete reactions are very common. The quenching or freezing impact of balance reaction deviates products from expected results, and produces a lot toxic gases, especially in composite explosives. In liquid explosives, addition of sensitizers with high reaction activities (such as nitroglycerine, hexagon, hydrazine nitrate, hydrazine perchlorate, aromatic explosives, etc.) helps to complete explosive reactions and reduce the production of toxic

Table 2.12 Toxic gas amount of explosion of ammonium nitrate

Ingredient (%)			Oxygen balance (%)	Toxic gas (L/kg)		
TNT	NH ₄ NO ₃	KNO ₃		CO	NO _x	CO Equivalent ^a
37.6	62.4	—	−15.3	125	2.7	142.6
22	78	—	−0.7	30.4	5.5	66
17.6	82.4	—	+3.5	20	13.3	106.5
17.6	62.4	20	+7.4	16.6	5.3	51.1

^a The conversion factor of NO_x to CO is 6.5

gases. Besides, addition of materials with catalytic activity (e.g., alkaline nitrate KNO₃) helps to significantly lower the nitrogen oxide amount of explosion products from ammonium nitrate explosives. Take pentaerythritol trinitrate as an example. Its oxygen balance is −34.49 %, and its detonation reactions are not complete. The reaction equation is below.



Whether the detonation reactions are complete or not is indirectly estimated from detonation parameters (e.g., detonation rate, brisance, etc.). If the processing time of trihydroxy methyl nitro methane is different, the measured brisance value is also different.

The compositions of liquid explosives are the main factors to produce toxic products. And the oxygen balance of liquid explosives is the determinant of toxic product amount. When the oxygen balance of explosives is zero, the explosion products are almost all H₂O, N₂, and CO₂. When the oxygen balance of explosives is positive, the excess oxygen oxidizes the nitrogen into nitrogen oxides, or converts to free oxygen, which increases the toxic ingredients. The main toxic ingredients are NO and NO₂/N₂O₄, while NO₂/N₂O₄ and N₂O₃ are the oxidation products of NO. When the oxygen balance of explosives is negative, carbon cannot be completely oxidized, which results in the production of CO gas. More the negative oxygen balance, more is the CO gas. Under certain conditions, the oxygen in the surrounding media affects the explosion. More oxygen, oxygen balance is positive. Less oxygen, oxygen balance is negative. To make the explosion reaction complete, it needs zero oxygen balance. This effect is especially obvious for the explosions under water.

Take solid explosives as an example to explain the influence of toxic gases by oxygen balance in explosion. Table 2.12 lists the experimental data of toxic gases released from explosion of ammonium nitrate mixtures.

The reactions of hydrogen and metal with oxygen are faster than the oxidation of carbon. For explosives, with the same amount of oxygen, if the ratio of carbon to hydrogen or carbon to metal is bigger, more CO is produced.

There are other factors for the production of toxic/poisonous composition/compounds. Imperfect explosion condition, noncomplete detonation, or blasting of explosive leads to production of large amount of NO₂. The posttreatment of

explosive also influences the production of toxic gas. Less CO and NO is produced if the compositions are mixed completely.

2.5.3 Countermeasures to Reduce the Toxicity of Liquid Explosive

Based on above factors of poisonous/toxic staff production, there are several methods to reduce the toxicity of liquid explosive. First is to control the emission of liquid explosive into earth and water to reduce the direct pollution and damage, while to reduce the production of large amount of poisonous gases, the oxygen balance, posttreatment and demolishing of liquid explosive are in full consideration. Such as, increasing and making sure enough ignition energy makes explosive to reach a stable detonation and react completely. High-power explosives with proper sensitivity are used as initiators, which is very important for explosives with lower sensitivity. Reasonable explosive charging geometries, waterproofing work of blasting supply, making sure the quality of charging and staff, and voiding half-explosion and deflagration all help to reduce the toxicity of explosion to the environment. Explosion produces an environment with high temperature and high pressure. Under these conditions, the mist (water in the air) reacts with CO to generate CO₂ and H₂, which effectively lowers the concentration of CO in blasting fame. Some nitrogen oxides are freely soluble in water, which reduces the emission of NO_x. In the application of explosives (e.g., rock mining), auto water spray helps to precipitate dust, and at the same time decreases the emission of poisonous gases, and lower down the toxicity of blasting fume.

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