

Discussions on Thermobaric Explosives (TBXs)

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Abstract: Aluminum is an important component of thermobaric explosives (TBXs). Because of the high ignition temperature of aluminum and its partial inertness during detonation, its optimum amount added to TBXs might differ, which can be used for distinguishing TBXs. According

to the theory on flow in a reactive medium, the parameter σ is introduced to explain the different reaction phenomena during the detonation process of TBXs. The σ value can be used to illustrate the detonation or afterburning of each reaction stage.

Keywords: Thermobaric explosives · Aluminum · Detonation · Afterburning

1 Introduction

Thermobaric explosives (TBXs) have recently aroused interest since they have potential use in warfare and defeating hardened targets [1,2]. Thermobaric weapons are used to produce heat and pressure effects instead of armor penetrating or fragmentation damage effects. The weapons are particularly effective in enclosed spaces such as tunnels, buildings, and field fortifications [3,4]. Its reactivity causes aluminum to be employed in explosive ordnance as a fine powder added to explosives to enhance their blast effect [5,6]. Generally speaking, the main affection of the large aluminum mass fraction improves spatial mixing of components in explosives with oxidizing gases in the detonation products, resulting in the release of more efficient afterburning energy. Although the effect of aluminum in thermobaric explosives has been identified, the high ignition temperature of aluminum is a key step in its application in TBXs. The reaction of aluminum and oxygen is affected by various factors such as the dispersion of aluminum particles, the scale of the aluminum particles or the coated/uncoated particles. In order to improve the whole impact of TBXs, the search for additional materials which can produce high enthalpy like aluminum [7] is a promising strategy to improve the energy of TBXs.

The reaction of a thermobaric explosive is divided into three stages and the parameter σ is introduced to explain the differences of the three stages. Because the combustion and detonation of TBXs do not only depend on chemistry, but are affected by a lot of other parameters such as the charge mass, charge geometry, etc, there are various thermobaric models introduced to simulate the propagation of the detonation products with the surrounding environment. This paper emphasizes the basic theory of the reaction mechanism of TBXs.

2 The Definition of Thermobaric Explosives(TBXs) and the Features

The US National Academy of Sciences has recognized that the fundamental physical phenomenon of thermobaric applications needs to be further understood, since there is a need to rapidly enforce the development of thermobaric weapons [4]. TBXs are generally regarded as solid fuel air explosives (SFAE), but explosives used as thermobaric explosives are usually oxygen poor and additional oxygen from air is required to achieve complete combustion of the charge. Moreover, TBXs cannot be considered as conventional aluminum containing explosives, because their most remarkable characteristic is the great mass of energy released through afterburning and combustion lengthens the duration of blast overpressure and increases the fireball. There is no obvious afterburning observed in conventional blast.

The present TBXs are formed by a metal composite consisting of a binder, a reactive metal (such as aluminum), an oxidizer, and a plasticizer; they may additionally contain a catalyst as effective component. The main effect of the large aluminum mass fraction is to improve spatial mixing of components in explosives with oxidizing gases in the detonation products, resulting in the release of more efficient afterburning energy. A thermobaric explosion consists of three stages, which are connected each other and which transfer subsequently to the next stage as a function of

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time and gas expansion. The three stages are: initial stage, anaerobic stage, and aerobic stage.

3 The Relative Details on the Explosion of TBXs with Aluminum

Compared to conventional secondary explosives, the shock wave generated from TBXs has a lower amplitude but a longer duration time (Figure 1). The reaction of aluminum on the detonation wave front is inert and the detonation velocity is below 6000 ms^{-1} . Because of the melting and vaporization of aluminum particles, the temperature and pressure of the C-J plane decrease and therefore the reaction rates of the other components are reduced. As a result, the reaction time is elongated and the reacting region increases. In the same time, the aluminum particles in TBXs are not well distributed. This is the other reason for the enlarged reaction region, since a multiple reaction process occurs. The secondary explosion experiences a momentary process, where the produced temperature and pressure rapidly increase. The mass fraction of aluminum in TBXs affects the volume of the explosives, and due to the existence of an oxide film, aluminum cannot react at the primary stage when TBXs create blast. The energy released in this stage is limited and the temperature and pressure are lower than in conventional explosives.

In TBXs, the shock wave component of thermobaric explosion mostly originates from the anaerobic process. The addition of aluminum plays an important role in this process.

The metal powder component of thermobaric explosives is critical for the ignition delay in the aerobic stage. The initial gas with the metal particle cloud expands and the particles start their reaction and burning in the explosive gases, uptaking oxygen from the residues of the base explosive. This happens very fast in the sub ms scale and can be seen as a separate peak after the initial shock front. The base ingredient used in TBXs has to have an oxidizing ca-

pability to support anaerobic combustion of the added metal to promote ignition conditions in the following aerobic stage.

It is well known that aluminum particles require high temperatures to be ignited (over 2000 K). A precise amount of aluminum has to be added to the TBXs. The proper addition may be decided by the two following factors. Because the declined energy caused by the inertness of aluminum in the first stage, one rule is that the amount of aluminum cannot influence the ignition: the sufficient energy from the primary detonation for the ignition temperature must be assured. The other important factor in the compound design is the oxygen-deficiency of the entire system. It is obvious that the optimized amounts of aluminum in various TBXs are different from each other. The particle size of aluminum and the surface coating may influence the ignition temperature of aluminum. Lowering the ignition temperature of aluminum particles can increase the efficiency of TBXs.

In the case of conventional blast, a large part of the energy is taken up by the break-up of the acceleration of the fragments, but the energy released in TBXs occurs over microseconds and the detonation velocities of TBXs ($3\text{--}4 \text{ km s}^{-1}$) are considerably lower than those of military high explosives (about 8 km s^{-1}). Besides the shock wave, TBXs usually release considerable energy ($1/4\text{--}1/3$ of the whole energy), which ends up as fireball in the last process [8].

In fact, the aerobic component of the explosion should be maximized in the holistic process, which is a difficult task. The metal combustion rate is considered to be an important parameter in generating high pressure levels in the last stage. Current methods to lower the ignition temperature include both reducing the particle size of aluminum and coating. In the development of thermobaric explosives, a faster reacting rate is needed and additionally the accelerated mixing of the composition with air or oxygen is a key factor for the manufacturing of TBXs.

4 TBXs and σ

The parameter σ is defined as follows:

$$\sigma = \Delta V/V - \beta \Delta H/C_p$$

where C_p is the heat capacity at constant pressure, ΔH is the heat changing term when the reaction proceeds, β is the thermal expansion coefficient and V is the volume of the system.

According to the theory on flow in a reactive medium [9], σ is a measure of the rate of transformation of chemical bond energy to molecular and bulk translation energy. In an unreacted explosive, the material entirely consists of the reactant in a metastable equilibrium. The parameter σ must be positive if the entire system is an explosive. The equation above is important because it shows both the volume

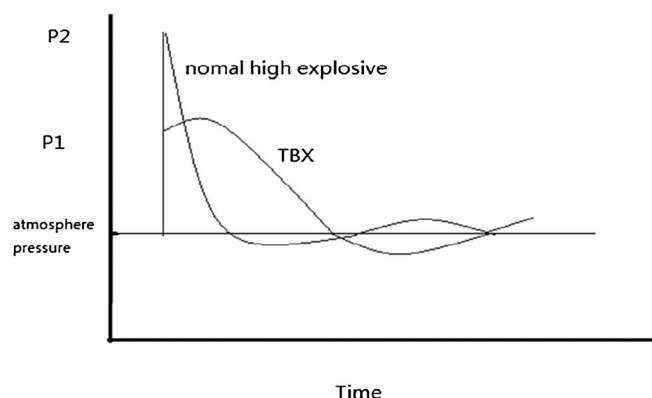


Figure 1. Pressure history of high explosive and thermobaric explosive detonations.

change and energy change of the reaction contributing to the explosive performance. All useful explosives have a positive heat release (negative ΔH), and the volume change is large enough to have practical consequences for the whole process.

As previously mentioned, the primary stage is attributed to the high explosive in TBXs. The volume can expand with the accordingly appearance of gases ($\Delta V/V > 0$, at the same time the heat release takes place ($\Delta H < 0$). The positive value of σ is a signal that the detonation indeed happens in this stage. The infinite products of the primary detonation are no more than five kinds gases [10] (H_2O , CO_2 , CO , H_2 , any excess oxygen forms O_2) and no free oxygen existed. This means that if aluminum particles begin and keep reacting in the subsequent stage, the oxidant has to come from the captured oxygen (H_2O , CO_2 , CO). It must be pointed out that the volume variation of the system is hardly exactly calculated because the aluminum particles may have no contact with the oxygen from the air and the reaction of degree is difficult to be judged. The value of σ cannot be predicted when the aluminum starts to join into the explosion. But the duration of the whole detonation is elongated with the reaction between aluminum and the gases produced by the first stage. Target damage effects are dependent on peak blast overpressure as well as on the duration (impulse) of the detonation. There are plenty of aluminum particles left when the second detonation is finished. The system inhibits the mixing of detonation gases with air and the rapid expansion of the detonation has a cooling effect before mixing with atmospheric oxygen occurs. The left aluminum keeping the activity has the opportunity to continue its reaction with the oxygen from the environment. In this progress, the formation of aluminum oxide (solid state) is abundant and the volume of the gases tends to be decreasing ($\Delta V < 0$) at some point even the constant pressure. The heat of oxidation is positive means the value of $\Delta H < 0$. Here the value of σ seems to be hard to decide but it is negative in fact. One of the reasons is that the volume change should be given prior consideration according to the theory on flow. The other powerful evidence is that the value of β has changed its sign in the beginning of this process.

$$\beta = \left(\frac{\partial V}{\partial T}\right)_p$$

In the first two stages, the volume increases with the temperature rise and the value of β is positive. In the last process, the value of V decreases when the temperature reaches a higher level under the condition that even the pressure keeps constant.

The negative value of σ indicates that the third stage of the reaction of TBXs cannot be a detonation process. This assumption was proved by experiment and is in agreement with the experimental results. The energy is only partly released during the initial detonation phase, which generates

high levels of fuel-rich products that undergo "afterburning" when mixed with the shock-heated air. The energy released through afterburning and combustion lengthens the duration of blast overpressure and increases the fireball. The high temperature and high pressure in the confined area arising from afterburning play an important role in the damage effect of TBXs. Smothering is also very effective when there are living organisms.

5 Afterburning

The third stage of the process is afterburning. When the explosion occurs in airtight environment, the energy release of the afterburning process can be divided into four types.

(1) Earlier reports [11–13] suggest that the metal powder in TBXs absorb heat but don't release energy on the detonation wave front. The reflection of metal powder with the product of detonation causes the first kind of afterburning.

(2) The metal and the detonation product react with oxygen from condensed air. Because of the large density gradient, the R-T (Rayleigh-Taylor) instability turbulent flow comes into explaining this mixture and burning step [14, 15].

(3) The air detonation wave reflected by the wall of the airtight environment reacts with the high speed fireballs generated by the above process. The turbulent flow burning [16–18] is increased and the boundary temperature of the fireball rises to reignite the mixture of the metal and the detonation products.

(4) The burning ball crashes to the barriers or the wall [11, 15] and the kinetic energy of the medium in the ball transfers into potential energy. The residual metal powder may be ignited to form a new burning region.

From these four types, it is considered that the afterburning begins with the start of the detonation. It doesn't stop and even gets intense until the detonation processes finish. The fireball and the blast produced in the earlier stages are able to reach corners and penetrate areas inaccessible to bomb fragments. Blast waves are intensified when reflected by walls and other surfaces. That causes the higher damage effect of TBXs compared to that of high explosives in confined conditions. The confined condition is important for TBXs, for limited space may benefit for the rising temperature and pressure produced by the reactions. The temperature and pressure cannot be hold even reduced in the open environment, the damage result decreases and may be inferior to the equal conventional high explosives.

6 Conclusions

The explosion process of TBXs consists of three stages: initial stage, anaerobic stage, and aerobic stage. Both the kind and amount of the metals added to TBXs are essential,

they are influencing the ignition temperatures of TBXs. The parameter σ is introduced to estimate the detonation occurrence. By this method, the first stage is a detonation process in contrast to the last stage. This is in coincidence to the experimental phenomenon that the third stage of the process is afterburning. The mixture is heated up by the detonation process and the afterburning process becomes intense when the detonation processes finish. The confined environment is as important as the ignition temperatures factor in the explosion of TBXs.

References

- [1] K. M. Jaansalu, M. R. Dunning, W. S. Andrews, Fragment Velocities from Thermobaric Explosives in Metal Cylinders, *Propellants Explos. Pyrotech.* **2007**, 32, 80.
- [2] N. H. Yen, L. Y. Wang, Reactive Metals in Explosives, *Propellants Explos. Pyrotech.* **2012**, 37, 143.
- [3] G. Neuneck, The Revolution in Military Affairs: Its Driving Forces, Elements, and Complexity, *Complexity*, **2008**, 14, p. 50.
- [4] A. E. Wildegger-Gaissmaier, Aspects of Thermobaric Weaponry, *ADF Heath*. **2003**, 4, 3.
- [5] C. K. Kim, J. G. Moon, J. S. Hwang, M. C. Lai, K. S. Im, Afterburning of TNT Explosive Products in Air with Aluminum Particles, *46th AIAA Aerospace Sciences Meeting and Exhibit*, Reno, NV, USA, January 7–10, **2008**, AIAA paper 2008-1029.
- [6] P. P. Vadhe, R. B. Pawar, R. K. Sinha, S. N. Asthana, A. Subhananda Rao, Cast Aluminized Explosives (Review), *Combust. Explos. Shock Waves (Engl. Transl.)* **2008**, 44, 461.
- [7] M. L. Chan, G. W. Meyers, *Advanced Thermobaric Explosive Compositions*, US Patent 6955732B1, the USA as Represented by the Secretary of the Army, Washinton DC, USA, **2005**.
- [8] W. Kicinski, W. A. Trzcinski, Calorimetry Studies of Explosion Heat of Non-Ideal Explosives, *J. Therm. Anal. Calorim.* **2009**, 96, 623.
- [9] W. Fickett, W. C. Davis, *Detonation*, University of California Press, London, UK, **1979**, p. 93.
- [10] P. W. Cooper, *Explosive Engineering: All Nitrogen goes to N₂*, New York, Wiley-VCH Inc. **1997**, p. 131.
- [11] M. F. Gogulya, M. A. Brazhnikov, Pressure and Temperature of the Detonation Products of Explosive Materials Containing Aluminum of Various Dispersities, *Russ. J. Phys. Chem. B* **2010**, 4, 773.
- [12] C. K. Kim, J. S. Hwang, K. S. Im, Numerical Simulation of Afterburning of Thermobaric Explosive Products in Air, *23rd International Symposium on Ballistics*, Tarragona, Spain **2007**, p. 201.
- [13] K. Benkiewicz, A. K. Hayashi, Aluminum Dust Ignition behind Reflected Shock Wave: Two-Dimensional Simulations, *Fluid Dynam. Res.* **2002**, 30, 269.
- [14] S. I. Anisimov, Y. B. Zel'dovich, Rayleigh-Taylor Instability of the Boundary Between Detonation Products and Gas in a Spherical Explosion, *Pis'ma Zh. Eksp. Teor. Fiz.* **1977**, 3, 1081.
- [15] S. I. Anisimov, Y. B. Zel'dovich, M. A. Inogamov, M. F. Ivanov, The Taylor Instability of Contact Boundary between Expanding Detonation Products and a Surrounding Gas, *Shock Waves, Explosions and Detonations*, **1983**, p. 218–227.
- [16] P. Wolański, Z. Gut, W. A. Trzciński, L. Szymańczyk, J. Paszula, Visualization of Turbulent Combustion of TNT Detonation Products in Steel Vessel, *Shock Waves* **2000**, 10, 127.
- [17] R. Hibert, F. Tap, H. E. Rabii, D. Thévenin, Impact of Detailed Chemistry and Transport Models on Turbulent Combustion Simulations, *Prog. Energy Combust. Sci.* **2004**, 30, 61.
- [18] M. F. Gogulya, M. N. Makhov, A. Yu. Dolgoborodov, M. A. Brazhnikov, V. I. Arkhipov, V. G. Shchetinin, Mechanical Sensitivity and Detonation Parameters of Aluminized Explosives, *Combust. Explos. Shock Waves (Engl. Transl.)* **2004**, 40, 445.

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