Journal of Hazardous Materials 301 (2016) 492–503

Contents lists available at ScienceDirect

Journal of Hazardous Materials

journal homepage: www.elsevier.com/locate/jhazmat

Nanoscopic fuel-rich thermobaric formulations: Chemical composition optimization and sustained secondary combustion shock wave modulation

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HIGHLIGHTS

- The art state for chemical structure optimization in terms of explosion power.
- Integration between thermochemical calculations and simulation modeling.
- Accurate simulation modeling of secondary combustion shock wave.
- Image processing of lethal fire-ball.
- An effective fire-ball duration up to 50 ms.

ARTICLE INFO

Article history:
Received 12 June 2015
Received in revised form 6 September 2015
Accepted 9 September 2015
Available online 14 September 2015

Keywords:
Thermobaric explosives
Nanoscopic metal fuel
Simulation modeling
Secondary combustion
Shock wave
Image analysis

ABSTRACT

Advanced thermobaric explosives have become one of the urgent requirements when targeting caves, fortified structures, and bunkers. Highly metal-based systems are designed to exploit the secondary combustion resulted from active metal particles; thus sustained overpressure and additional thermal loadings can be achieved. This study, reports on a novel approach for chemical composition optimization using thermochemical calculations in an attempt to achieve the highest explosion power. Shock wave resulted from thermobaric explosives (TBX) was simulated using ANSYS® AUTODYN® 2D hydrocode. Nanoscopic fuel-rich thermobaric charge was prepared by pressing technique; static field test was conducted. Comparative studies of modeled pressure–time histories to practical measurements were conducted. Good agreement between numerical modeling and experimental measurements was observed, particularly in terms of the prediction of wider overpressure profile which is the main characteristics of TBX. The TBX wider overpressure profile was ascribed to the secondary shock wave resulted from fuel combustion. The shock wave duration time and its decay pattern were acceptably predicted. Effective lethal fire-ball duration up to 50 ms was achieved and evaluated using image analysis technique. The extended fire-ball duration was correlated to the additional thermal loading due to active metal fuel combustion. The tailored thermobaric charge exhibited an increase in the total impulse by 40–45% compared with reference charge.

1. Introduction

The shock waves of conventional explosives are localized and decrease significantly while moving away from the explosion center, consequently conventional explosives are of limited effects on fortified individuals inside caves and bunkers [1]. Recently, thermobaric explosives (TBX), particularly highly metal-based systems are designed to exploit the secondary combustion, which can cause sustained overpressure and additional thermal loadings [2,3]. TBX can act as a source of lethal energy against soft targets in confined spaces [4], they exhibit a potential effect as they are able to add to the total impulse with in tens of millisecond inside a building or up to one second with in a tunnel [4]. This is why; TBX have received lots of attention. In general, TBX consist of central charge (core) usually high explosive, and external secondary charge (fuel-rich formulation) [5]. Therefore, the detonation of TBX accompanied by a dual action; anaerobic action (without air oxygen) inside the conventional high explosive core, aerobic delayed burning action of the fuel mixture of the outer charge which depends mainly on the surrounding air [6–8]. The fuel burning via reaction with the

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http://dx.doi.org/10.1016/j.jhazmat.2015.09.019

Table 1
The Chemical compositions of investigated thermobaric formulations.

TBXabbrev.	Aluminum(Al)(Wt%)	Monopropellant(MP)(Wt%)	Hexogen(RDX)(Wt%)	Ammonium perchlorate(Wt%)	Polymeric binder(Wt%)
TBX 1	50	30	0	14	6
TBX 2	50	20	10	14	6
TBX 3	50	10	20	14	6
TBX 4	40	35	5	14	6
TBX 5	40	25	15	14	6
TBX 6	40	15	25	14	6

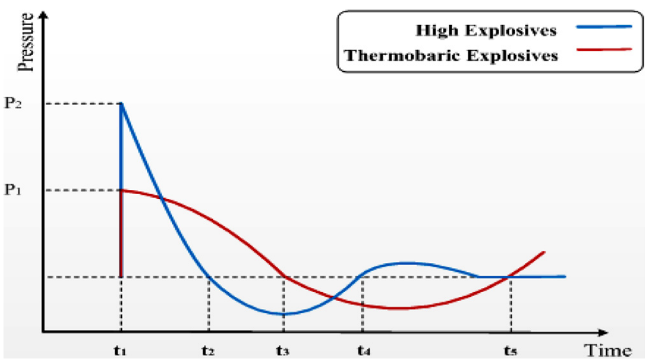

Fig. 1. Pressure–time relation for high explosive (HE) to that of thermobaric explosives (TBX) [1].

detonation products as well as oxygen from the air raises the temperature of the gaseous product cloud, and strengthens the shock wave [4,9,10]. Pressure–time (P–t) history of TBX and its difference from classical high explosive are represented in Fig. 1.

Even though, the peak overpressure (P_1) for TBX is lower than (P_2) for conventional explosives; it lasts for longer time. Consequently, the total impulse (integrated area under the curve) for TBX is much higher than that for conventional explosives [11]. This is why TBX cause effective damage to structures and fortified persons in caves [12,13]. The tailored fuel-rich secondary charge can cause depletion of oxygen in the confined areas causing suffocation of fortified persons in caves [14]. Nanoscopic aluminum fuel tends to react with air oxygen as well as with the decomposition gases adding additional thermal loading [15,16]. The extra heat gained by incorporating the excess aluminum into the mixture is substantial [17]. The reaction of excess aluminum with atmospheric oxygen or decomposition gasses as represented by Eqs. (1)–(5) [6,13].

$$2Al_{(s)} + 3/2O_2 Al_2O_{3(s)} + 1700\,KJ/mol \quad (1)$$

$$2Al_{(s)} + 3CO_{(g)} Al_2O_3 + 3C + 1251\,kJ/mol \quad (2)$$

$$2Al_{(s)} + 3H_2O_{(g)} Al_2O_{3(s)} + 3H_{2(g)} + 866\,kJ/mol \quad (3)$$

$$2Al_{(s)} + 3CO_{2(g)} Al_2O_3 + 3CO + 741\,kJ/mol \quad (4)$$

$$2Al_{(s)} + N_{2(g)} 2AlN + 346\,kJ/mol \quad (5)$$

This series of exothermic reactions represents the secondary combustion pathway according to reaction spontaneity and reaction rate [17,18]. It is commonly assumed that the nitridation channel (5) is much slower than oxidation channels (1–4). Thereby, a large amount of energy is liberated during reactions of Al with primary detonation products, leading to sustained thermal loading [18,19]. Nano-scale aluminum particles have the potential to initiate the secondary combustion process due to the increased interfacial surface area, and reactivity [17]. The smaller the particle size of aluminum the more sensitive and reactive it will be [17]. Furthermore, nanoscopic aluminum surfaces are readily oxidized by the oxygen in the air, and a tight surface coating of aluminum oxide (Al_2O_3) is formed that protects the inner metal from further oxidation (Fig. 2).

Hence, aluminum powder can be stored for extended periods with little loss of reactivity due to air oxidation [17]. Sustained combustion could be achieved by the release of coarse burning aluminum flakes (called sparks) [17,20]. It is widely accepted that the reaction of Al is relatively slow in the Chapman–Jouguet plane due to coating of Al particle by Al_2O_3 having a high melting point (2030 °C), which impedes its reactivity. Consequently the combination between ultrafine aluminum and coarse particles seems to be vital in an attempt to achieve high packing density, secondary charge ignition, efficient secondary combustion, as well as long duration [2,6].

On TBX detonation, the dispersing charge will explode with explosion temperature of 3380 °C [21]. This detonation temperature is more than enough to bring the oxidizer of the secondary charge to the decomposition temperature releasing free oxygen,

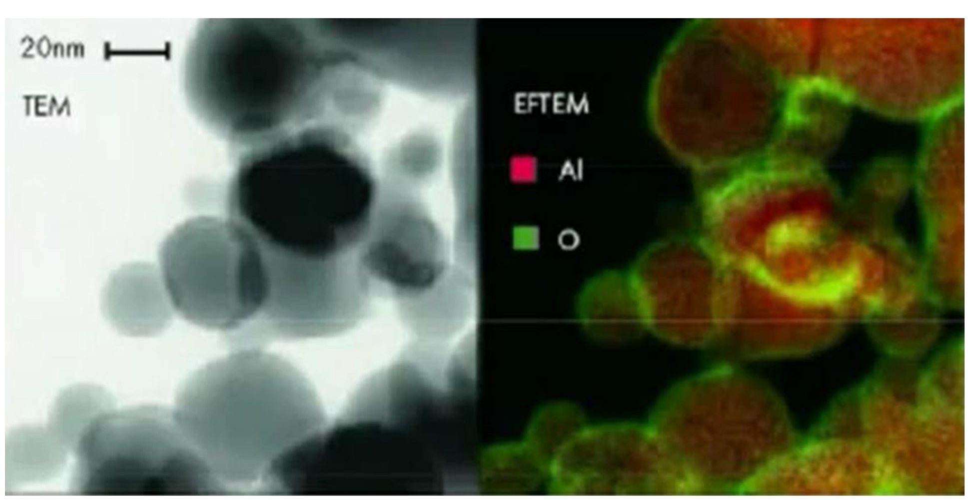

Fig. 2. Aluminum nanoparticles with passivated layer of Al_2O_3 [17].