



Thermobaric effects formed by aluminum foils enveloping cylindrical charges



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ABSTRACT

Conceptually new cylindrical charges enveloped by Al foils have been designed and their thermobaric effects, due to simultaneous fragmentation and combustion of the foils, have been experimentally determined. The fragmentation processes of Al foil was supported by numerical simulations. It has been shown that the quasistatic pressures (QSP) for phlegmatized RDX (RDX_{ph}) enveloped with Al-coated plastic foils are higher than that of the pure RDX_{ph} , due to combustion of these foil fragments in a thermobaric explosion. The QSP generated by Al–Ni foils enveloping RDX_{ph} was found to be much lower than performance of other foils, possibly due to relatively inert nature of Ni. In a small detonation chamber, the charges of RDX_{ph} /Al foil (RDX_{ph} /Alf) produced even higher experimental maximum peak pressure (Δp_{max}) than the charges that contained Al powder (Al_p). In a closed bunker, the impulse amplitudes of RDX_{ph} enveloped by aluminized polyethylene (Al-PE) foils and RDX_{ph} enveloped by 100 μm Alf (Alf100) charges are much lower than those of the other charges. It was found that the charges enveloped by Al foils have even larger Δp_{max} than that of RDX_{ph} / Al_p charges, indicating that the Alf could generate better blast performances than the Al_p . The simulations indicate that the observed blast enhancement is dependent not on the thickness, but on the size of surrounding space. The thermobaric fire-ball generated by 40 g RDX /Alf charge could sustain combustion up to 40 ms, reaching a maximum radius of about 2.4 m.

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1. Introduction

Thermobaric explosives (TBXs), also regarded as solid fuel-air explosives (SFAE), over the years have created a great interest since they are highly destructive in enclosed spaces such as underground constructions, tunnels, and field fortifications [1–4]. Thermobaric effects refer to heat and pressure effects, instead of armor penetrating or fragmentation damage effects [5]. In TBX formulations, a large proportion of metal fuels are usually used to generate the heat in a secondary combustion after the detonation of the main charge. In particular, Al is the most widely used metal for this purpose [6]. Due to its high ignition temperature (T_i) and partial inertness during detonation, the optimum amount of Al might differ, depending on the type and content of the explosive fillers in TBXs. However, the efficient use of Al in energetic compositions including TBXs remains challenging due to several reasons.

One such example is the use of micrometer-sized Al that may agglomerate, resulting in lower combustion efficiency and increased two-phase flow losses [7]. The use of nano-sized Al (nAl) may improve the combustion performance and reduce the particle size of the final agglomerated products, but it would reduce the energy release due to a higher inert Al_2O_3 content. Moreover, a very high surface area (10–50 $\text{m}^2 \text{g}^{-1}$) of nAl particles can lead to rheological problems during processing (e.g. difficulty in casting) [8]. The combination of nAl (e.g. 75 nm) and coarse Al (e.g. 250 μm) particles with equal fractions may partially solve these problems [9].

In order to improve the heat releases and combustion efficiency of nAl in both propellants and TBXs, many strategies have been developed. For instance, energetic blends of nAl particles with liquid perfluorocarbon-based oxidizers, such as perfluoropolyethers (PFPE) were prepared. In this way, exothermic reaction on the surface between fluorine and the Al_2O_3 shell could be activated, and hence the reactivity of nAl particle is improved, leading to a significant increase in the flame speed. It has been proved that the oxygen and fluorine have equal probability to react with Al [10,11]. In addition, the ignitability of the Al/ polytetrafluoroethylene

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(Al/PTFE) composite can be improved by mechanical activation such as milling. The activated samples can be readily ignited by using a butane flame, while the physical mixtures of micro-sized Al and PTFE are only ignitable with an exposure to continuous flame [12]. Another facile way of promoting the reactivity of Al_p is to introduce a liquid perfluorinated or fluoro-oligomer by physisorption on the surface of Al_p [13,14]. When fluorine replaces oxygen as the oxidizing agent, AlF₃ is formed instead of Al₂O₃, both of which are thermodynamically stable with heats of formation of 1510 and 1676 kJ mol⁻¹, respectively [15]. In addition to fluoropolymer, the activation of Al_p could also be achieved by combining with the other metals. For instance, the equiatomic Al–Ni mixtures after milling can reduce exothermic onset of Al_p by as much as 300 °C [16]. The use of Al–Ni composite in a solid propellant could reduce the agglomeration of Al_p and decrease its ignition delay.

Generally, two major issues may affect the performances of aluminized TBXs. The rule is that there must be sufficient energy from the primary detonation for achieving the T_i of the Al, while the entire charge should be oxygen-deficient. As mentioned above, the particle size of Al and the surface coating may influence the T_i of Al, and lowering the T_i of Al particles can increase the performances of TBXs [17]. In order to fulfill the above-mentioned requirements, the charge designs in terms of compositions and structures are equally important. Recently, several novel oxygen-deficient compositions have been developed, which contains a reactive metal, binder, and plasticizer, sometimes with addition of a catalyst [18]. Moreover, a class of charges using an annular design was developed, where a cylindrical shell of a metalized charge surrounds the high explosive charge [19]. A recent study by Trzciński and coworkers regarding the explosion of an annular charge showed the improved performance as a TBX charge [20–23]. It was composed of a phlegmatized RDX (RDX_{ph}) core and a layer of ammonium nitrate (AN)/Al particles mixture. The influence of Al contents and particle sizes on a quasi-static pressure (QSP) of explosion was further studied by the same group [24]. In fact, the core explosive charge may generate enough energy to break the out-layer metals and simultaneously ignite the fragmented metal particles in surrounding air. It was further found that, even a significant mass of the steel case of an explosive charge can be burned to enhance air blast in the chamber [25]. In this work, a conceptually new design of TBX was developed and tested. In this new design, the Al powder inside the conventional TBX charges was removed, and replaced by enveloping the core charge with Al foils. The general idea behind this design was that upon detonation, the layers of Al foil would be fragmented into micron-sized particles, and subsequently ignited in the air, generating thermobaric effect. The Al foils are simply made of pure Al or activated aluminized composites containing polymers or Ni foil as mentioned above, in order to decrease the T_i of the Al. The experiments in this work were conducted in both open field and confined spaces (including 0.15 and 40 m³ chambers). In addition to straightforward preparation of newly designed TBXs from the commercially available Al foils and aluminized plastic films, their performances have been tested by various experimental techniques. The observed performances of these new charges showed the significant advantages of previously known designs.

2. Experiments and theory

2.1. Charge compositions and quasi-static pressure measurements

The cylindrical charges used in QSP tests had an explosive core with a diameter of 20.0 mm. It was composed of two pellets of RDX/wax 94/6 composition (RDX_{ph}). The pellets had a density of 1.66 g cm⁻³ and were glued together. The mass of RDX_{ph} cores was 25.0 g. The external layer (envelope) included of Al foil (Alf), Al

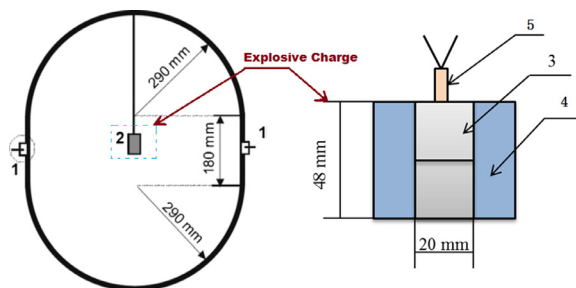


Fig. 1. Schematic of the investigated layered charge and the 0.15-m³ explosion chamber (side view): 1 – pressure gauges, 2 – explosive charge, 3 – RDX_{ph} (25 g), 4 – envelope (40 g), 5 – fuse.

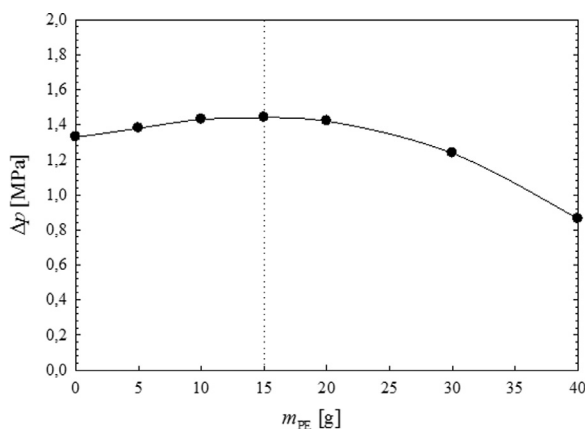


Fig. 2. Dependence of overpressure in the 0.15-m³ chamber on the mass of PE foil in the Al/PE envelope.

Table 1

Compositions of the charges for QSP tests.

Charge symbol	Mass of the component [g]					
	RDX _{ph}	Alf	PTFE	Ni	PE	Alp
RDX _{ph}	25.0	–	–	–	–	–
RDX _{ph} +Al foil (Alf)	25.0	40.0	–	–	–	–
RDX _{ph} +Al/PTFE foils	25.0	10.0	30.0	–	–	–
RDX _{ph} +Al/Ni foils	25.0	23.8	–	16.2	–	–
RDX _{ph} +Al/PE foils	25.0	25.0	–	–	15.0	–
RDX _{ph} +Al powder	25.0	–	–	–	–	40.0

powder (Al_p) or combinations of Al/PTFE, Al and polyethylene foils (Al/PE), Al and nickel foils (Al/Ni). The mass of the external layer (envelope) was 40 g, which were wound alternately and uniformly in the case of two component layers. Figure 1 shows a cross section of an explosion chamber and cylindrical layered charge applied in the tests.

The thickness of Al was 10 or 100 μm, while the PTFE, PE and Ni foils were 200, 100 and 125 μm, respectively. Mass ratio of Al/PTFE and Al/Ni out-layers corresponded to the stoichiometry of the following reactions: 3C₂F₄+4Al=4AlF₃+6C and 3Al+Ni=NiAl₃. In the case of Al/PE envelope, mass fraction of PE and Al foils was determined using CEETAH code [26]. The calculated overpressure in a 0.15-m³ chamber filled with air after detonation of a charge containing 15 g PE and 25 g Al had the maximal value of approx. 1.4 MPa, Fig. 2.

The purity of Al_p used in the experiments was above 99.5%, and its particle diameters were below 44 μm (325 mesh). The powder was placed in a thin-walled paper tube of 38 mm in diameter, surrounding the RDX_{ph} core (Table 1).

QSP tests were performed in a chamber of about 0.15 m³ volume, which was filled with air at pressure of 0.1 MPa. The

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