

A Method to Investigate the Confined Explosion of Thermobaric and Enhanced Blast Explosives

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ABSTRACT: A method to investigate the confined explosion of metallized explosive formulations is reported in this manuscript. New RDX-based composites in form of macroscopic granules were used during the study. Aluminum powder was chosen as a metallic fuel. Two different particle sizes have been investigated. Pressed and layered cylindrical charges containing these composites were prepared. The pressed charges are considered as enhanced blast explosives and the layered ones as thermobaric explosives. To estimate and quantify the heat of explosion and the effective aluminum consumption during the explosion of such formulations, tests were carried in 0.15 m³ closed explosion chamber. Firstly the quasi-static pressures generated by the charges were determined using pressure gauges and after by combining experiments with thermochemical calculation using CHEETAH code, the real energy of the explosion and the effective amount of the aluminum participating in the afterburning reactions is quantified. Results showed that still important amount of the energy which comes from the aluminum combustion is not completely and efficiently participating in the explosion process and that the followed methodology can be used as a reliable tool to optimize the composition of metallized explosives to obtain the highest performances.

KEYWORDS -Enhanced Blast Composite, Thermobaric Explosives, Aluminum, Metallized Explosives, Confined Explosion.

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I. INTRODUCTION

The first source of energy during explosion comes from the detonation; later, depending on the explosive, more or less important amount of energy can be available and could be released during the afterburning combustion process [1]. This late time energy may be efficiently used and can significantly enhance the blast and the thermal performances of the explosive [2,3]. For this purpose, chemically active metals with high combustion enthalpies are of interest as high energy density materials and they are added to the basic compositions. This method is generally used in the defense and aerospace industries [4,5]. The combustion energy of the reactive metals is three to five times higher comparing to the detonation energy of classical explosives [2], despite that their reaction rate is not fast enough to take part in the reactions in the detonation zone, they may react with detonation products of the explosion and oxygen from air over a much longer timescale than the detonation of the explosive itself and hence contribute to the work done by the expanding combustion products and significantly increase the explosion energy. In underwater applications, the reactions of metals with water also contribute to the bubble energy [5,6].

The influence of the metallic fuel on the energetic performances of the explosives formulations have been extensively investigated, aluminum powder is commonly used because it has a high energy density, is relatively inexpensive, easy to produce, and has a low toxicity. Aluminized explosives have been used in various formulations since the beginning of the 20th century [2,5,7,8]. Thermobaric explosives (TBXs) and enhanced blast explosives (EBXs) belongs to this type of explosive formulations. They are new aluminum-enriched systems developed to overcome the shortcomings of classical explosive. Unlike high explosives; they are extremely effective and destructive in enclosed spaces. The detonation of such materials is accompanied by three stages, a first and a second short anaerobic reaction stages and a third long aerobic combustion stage. Lasting tens of milliseconds, this last combustion stage, is characterized by the reaction of the

aluminum contained in these explosives with detonation products and oxygen from air. The result is a long lasting pressure wave and a late important thermal effect. When detonated in closed spaces shock wave reflections and mixing of the metallic fuel with detonation products and air enhance more the afterburning reactions of the aluminum fuel leading to a considerable increase in the generated quasi-static-pressure (QSP) and in the fireball temperature [9-14].

However, evidences exist that not all the energy which is available in the aluminum fuel is completely and effectively used during the explosion of such formulations. Unfortunately, still part of this additional heat is not used optimally and this can drastically affect the performances of TBXs and EBXs compositions. Theoretical and experimental studies are undertaken in order to understand and describe the process of the fuel particles reaction with the gaseous detonation products and to determine the conditions that must be satisfied for the explosion of the fuel cloud particles in air. The final composition must be a compromise between reaction rate, the optimal dispersion of fuel and non-oxidized detonation products and the ability to initiate combustion of the mixture of aluminum fuel and air. The explosion process must be sufficiently slow to disperse the aluminum powder, but fast enough to guarantee that the combustion process is not interrupted. If the process is too fast then the fuel is too widely dispersed and heat density generated is too small to initiate the subsequent oxidation of the fuel particles [2,6-7,9,15-25]. The main objective is to make the aluminum fuel to burn completely and with adequate rate that the energy release could be used entirely during explosion (in the anaerobic stage to strengthen the blast wave and in the aerobic stage to increase temperature and pressure of the fireball). However, this task is hard to reach since till now there is no a reliable quantitative method to determine or even to estimate the real amount of the fuel which really burnt and was used effectively during the whole explosion process. This complicates the composition optimization process and makes research more expensive and time consuming.

In this paper, a method which combines experiment with thermochemical calculation to determine the effective percent of the aluminum consumption as well as the explosion energy during aluminized explosives detonation in closed space is proposed, described and discussed. This method can also be used for the same purpose with compositions containing other metal additives than aluminum, alloys or mixtures. The tested formulations are new aluminized composite which belongs to the family of TBXs and EBXs.

II. EXPERIMENTAL APPROACH

2.1 The composite material

Large macroscopic multi-components energetic granules elaborated by the “wet method” [26] were used to prepare the investigated charges (Fig. 1). These composite granules are spherically shaped with a diameter ranging from 1.1 to 1.6 mm and contain a number of crystals of cyclo-1,3,5-trimethylene-2,4,6-trinitramine (RDX) as a high explosive powder, ammonium perchlorate (AP, NH_4ClO_4) as an oxidizer, aluminium (Al) as a metallic fuel, and the whole is consolidated by Viton (copolymer of vinylidene fluoride and perfluoropropylene) as a binder. Names and composition of the composite granules are given in Table 1. Crystalline AP with particle sizes below 0.8 mm and two types of aluminum powder were used. The first type Al1 with particle size below 44 μm (325 mesh) and the second Al2 with particle sizes between 44 and 149 μm (325 to 100 mesh).

Table 1. Name and composition of the used composite granules.

Granule name	11-A	12-A	21-A	22-A
Ingredients	Composition (wt. %)			
RDX	50.0	18.2	50.0	18.2
AP	10.0	18.2	10.0	18.2
Al1	30.0	54.5	-	-
Al2	-	-	30.0	54.5
Viton	10.0	9.1	10.0	9.1





Fig. 1. Camera and optical microscope photos of the composite granules 21-A

2.2 Characteristics of charges

Two kinds; layered and pressed cylindrical charges containing the different composites were prepared. All charges had the same mass of 43 g and the same total composition. The composites containing 50% of RDX were pressed using a hydraulic press into 25 mm diameter cylindrical pellets. This type of charges is named hereafter as pressed charges TBX-x, where symbol x is the name of the composite. Photography as well as a cross section of the pressed charges is shown in Fig. 2. TBX-11-A and TBX-21-A had a density of 1.87 and 1.90 g/cm³ respectively. The second kind of charges is described in Fig. 3. The cylindrical layered charge consists of a core and an external layer. The core is composed from two cylindrical pellets of RDX phlegmatized with 6% of wax (RDXph). The total mass of the core was 18.3 g, its diameter and density were 16 mm and 1.69 g/cm³, respectively. These charges are named hereafter as layered charges TBX-12-A and TBX-22-A. The external layer had a mass of 24.7 g of a given composite. The external cylinder was a paper tube having a thickness of about 2 mm and an internal diameter of 30 mm. Masses of the core and the external layer were selected in such a way that the total mass of charges and percentage of each component are identical to the pressed charges (50% RDX, 30% Al, 10% AP and 10% binders (wax+Viton))



Fig. 2. Schematic and photo of the investigated pressed charges: 1 – composite, 2 – detonator

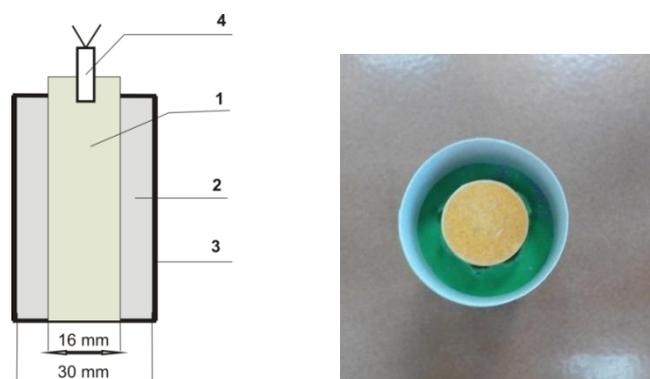


Fig. 3. Schematic and photo of the investigated layered charge: 1 – RDXph, 2 – composite, 3 – paper tube, 4 – detonator

2.3 Experimental site

Confined explosion investigations were performed in a closed explosion chamber of 0.15 m³ in volume. Dimensions of the explosion chamber are shown in Fig. 4. A charge was hung in the center of the chamber and a

standard fuse was used to initiate detonation. Primary tests were carried in air atmosphere under normal pressure of about 0.1 MPa and at ambient temperature. Then, tests were carried in argon atmosphere under the same conditions. In this case, in order to expel air from the chamber, this latter was filled with argon up to the pressure of 0.25 MPa and emptied three times. After filling last time to pressure of 0.1 MPa, the chamber was ready for tests under argon atmosphere. In both atmospheres, air and argon, at least three tests were performed for each investigated charge. Signals of overpressure from two piezoelectric gauges (PCB Piezotronics, model 102A and 102B) located at the chamber wall were recorded by a digital storage scope. The surface of pressure sensors was covered by a plastic material to prevent them from jets and hot explosion products.

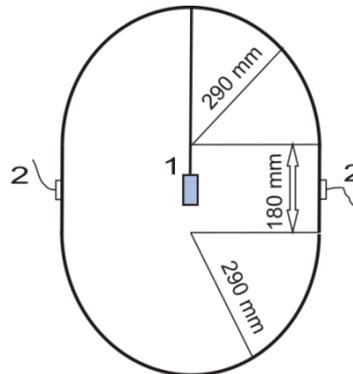


Fig. 4. Schematic of the 0.15 m³ explosive chamber (side view): 1 – explosive charge, 2 – pressure gauges

III. METHOD, RESULTS AND DISCUSSION

3.1 Quasi-static pressure determination (QSP)

Fig. 5 and 6 show exemplary overpressure history profiles recorded for TBX-11-A charges placed inside the explosion chamber in air and argon atmospheres respectively. Basically, six overpressure profiles could be recorded for each charge, however, in a few cases the pressure was not recorded at all by the gauges or, sometimes, the obtained signal did not have a physical meaning. The overpressure history records have oscillating nature caused by shock reverberations at the chamber wall, shock reverberations inside the chamber, turbulences of the hot explosion products and vibrations of the measuring system. Amplitude of these oscillations decreases with time. Equation (1) was used for overpressure history approximation (Δp) where a , b , c and d are constants, t is time.

$$\Delta p = ce^{-dt} + a(1 - e^{-bt}) \quad (1)$$

Function (1) reaches a maximum value Δp_{max} for a time t_{max} (Equation (2)). If t_{max} is outside the investigated interval of time, Δp_{max} is equal to the constant c corresponding to $t = 0$ s. Values of Δp_{max} (QSP) determined on the basis of at least three overpressure histories recorded in chamber filled with air and argon are summarized in Table 4.

$$t_{max} = \ln\left(\frac{ab}{cd}\right) \frac{1}{b-d} \quad (2)$$

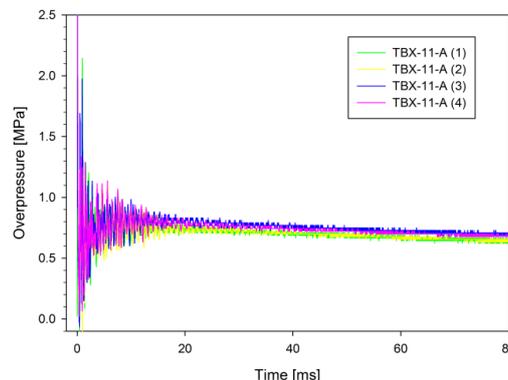


Fig. 5. Experimentally recorded overpressure profiles from the charge TBX-11-A detonated in air atmosphere

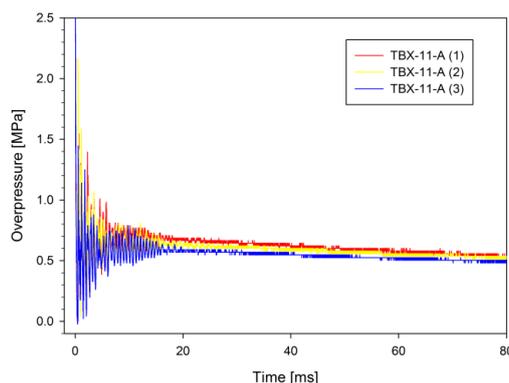


Fig. 6. Experimentally recorded overpressure profiles from the charge TBX-11-A detonated in argon atmosphere

3.2 Estimation of the explosion heat and the effective aluminum consumption

The heat of explosion Q_v and the degree of aluminum consumption in TBX-A charges detonated in air and argon atmospheres have been determined on the basis of the experimentally determined QSP and thermochemical calculations according to the following procedure. Firstly, thermochemical calculations were made to estimate the theoretical equilibrium overpressure in the explosion chamber filled with air or argon assuming the aluminum activity varying from 0 to 100% (percentage of aluminum which can participate in the reactions with a path of 10). These calculations were run using the CHETTAH code with modified library used for this purpose with the set of values of the BKWC parameters: $\alpha = 0.50$, $\beta = 0.40$, $\kappa = 10.86$ and $\Theta = 5441$ K [27,28]. Fig. 7 shows the theoretical variation of the overpressure as a function of the activity of aluminum. After that, for each percentage of the active aluminum, the composition of the detonation products was determined. The results are presented in Table 2 and 3. Only the products with concentrations which can affect the calculation of explosion heat are presented. The products which are not in gaseous state are followed by (liq) for liquid state and (sol) when they are in solid state in the explosion products.

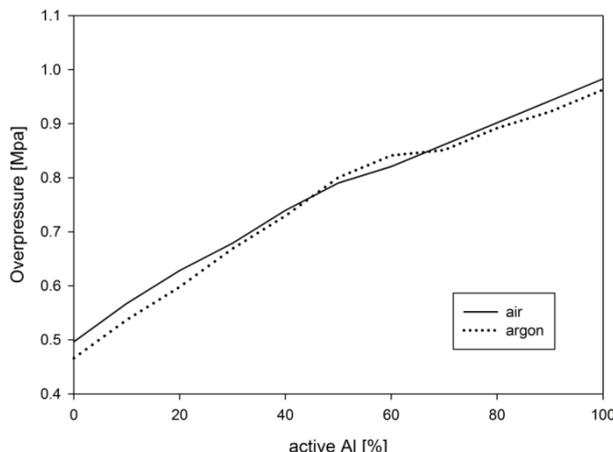


Fig. 7. Theoretical overpressure profiles variation with the activity of aluminum for TBX-A charges in air and argon.

Table 2. Composition and concentrations of detonation products for charges detonated in air atmosphere related to the activity of aluminum.

Active aluminum [%]	Product concentration [mol/kg]								
	H ₂ O	CO ₂	COF ₂	HCl	NO	NO ₂	CO	Al	Al ₂ O ₃
0	1.79	1.56	3.32 10 ⁻¹	1.16 10 ⁻¹	3.9 10 ⁻²	3.8 10 ⁻⁴	1.1 10 ⁻⁵	2.13 (liq)	0.00
10	1.79	1.56	3.32 10 ⁻¹	1.16 10 ⁻¹	7.7 10 ⁻²	5.04 10 ⁻⁴	9.96 10 ⁻⁵	1.91 (liq)	0.110 (sol)
20	1.79	1.56	3.32 10 ⁻¹	1.16 10 ⁻¹	1.36 10 ⁻¹	6.25 10 ⁻⁴	5.72 10 ⁻⁴	1.70 (liq)	0.210 (sol)
30	1.78	1.56	3.32 10 ⁻¹	1.16 10 ⁻¹	2.12 10 ⁻¹	7.39 10 ⁻⁴	2.36 10 ⁻³	1.49 (liq)	0.319 (sol)
40	1.78	1.55	3.32 10 ⁻¹	1.16 10 ⁻¹	3.04 10 ⁻¹	8.42 10 ⁻⁴	7.61 10 ⁻³	1.28 (liq)	0.425 (sol)
50	1.78	1.54	3.32 10 ⁻¹	1.16 10 ⁻¹	4.10 10 ⁻¹	9.31 10 ⁻⁴	0.0202	1.06 (liq)	0.532 (liq)
60	1.78	1.52	3.32 10 ⁻¹	1.16 10 ⁻¹	4.71 10 ⁻¹	9.60 10 ⁻⁴	0.0332	0.851 (liq)	0.638 (liq)
70	1.77	1.50	3.32 10 ⁻¹	1.16 10 ⁻¹	5.54 10 ⁻¹	9.82 10 ⁻⁴	0.0583	0.638 (liq)	0.744 (liq)

80	1.76	1.46	3.32 10 ⁻¹	1.16 10 ⁻¹	6.61 10 ⁻¹	1.04 10 ⁻³	0.105	0.425 (liq)	0.851 (liq)
90	1.75	1.39	3.32 10 ⁻¹	1.16 10 ⁻¹	7.70 10 ⁻¹	1.08 10 ⁻³	0.177	0.213 (liq)	0.957 (liq)
100	1.74	1.30	3.32 10 ⁻¹	1.16 10 ⁻¹	8.76 10 ⁻¹	1.10 10 ⁻³	0.263	0.00	1.04 (liq)

Table 3. Composition and concentrations of detonation products for charges detonated in argon atmosphere related to the activity of aluminum.

Active Al [%]	Product concentration [mol/kg]										
	H ₂ O	CO ₂	COF ₂	HCl	CO	COHF	F ₃ CH	Al ₂ O ₃	F ₂ CH ₂	AlN	Al
0	0.773	0.442	0.253	0.126	0.773	3.54 10 ⁻⁴	3.04 10 ⁻³	0.00	0.00	0.00	1.65 (liq)
10	0.669	0.297	0.254	0.126	0.917	4.18 10 ⁻⁴	2.84 10 ⁻³	0.0826(sol)	0.00	0.00	1.49 (liq)
20	0.536	0.183	0.253	0.126	1.03	4.88 10 ⁻⁴	3.22 10 ⁻³	0.165 (sol)	0.00	0.00	1.32 (liq)
30	0.374	0.100	0.211	0.126	1.12	5.59 10 ⁻⁴	4.47 10 ⁻³	0.248 (sol)	0.00	0.00	1.16 (liq)
40	0.190	0.0393	0.245	0.126	1.18	6.27 10 ⁻⁴	8.35 10 ⁻³	0.330 (sol)	0.00	0.00	0.991 (liq)
50	0.020	3.43 10 ⁻³	0.180	0.126	1.23	5.96 10 ⁻⁴	0.0513	0.413 (sol)	0.00	0.00	0.83 (liq)
60	3.15 10 ⁻⁴	5.47 10 ⁻⁵	0.0264	0.126	1.29	2.33 10 ⁻⁴	0.153	0.455(sol)	2.35 10 ⁻³	0.0803(sol)	0.661 (liq)
70	3.19 10 ⁻⁴	5.44 10 ⁻⁵	0.0270	0.126	1.29	2.37 10 ⁻⁴	0.152	0.455 (liq)	2.30 10 ⁻³	0.246 (sol)	0.495 (liq)
80	3.49 10 ⁻⁴	5.65 10 ⁻⁵	0.0300	0.126	1.29	2.53 10 ⁻⁴	0.151	0.455 (liq)	2.11 10 ⁻³	0.412 (sol)	0.330 (liq)
90	3.70 10 ⁻⁴	5.76 10 ⁻⁵	0.0323	0.126	1.29	2.6 10 ⁻⁴	0.149	0.454 (liq)	1.98 10 ⁻³	0.577 (sol)	0.165 (liq)
100	3.96 10 ⁻⁴	5.89 10 ⁻⁵	0.0352	0.126	1.28	2.82 10 ⁻⁴	0.147	0.453 (liq)	1.83 10 ⁻³	0.744 (sol)	0.00

The theoretical explosion heat per gram of explosive for different aluminum activity can be calculated from the equation:

$$Q_v = -\left\{\sum_{i=1}^k n_i \Delta H_i - \Delta H_{com}\right\} \cdot \frac{m_{com}}{m_{exp}} \tag{3}$$

where,

- Q_v is the heat of explosion for a certain activity of aluminum[J/g],
- k is the number chemical species existing in the detonation products given by the thermochemical code,
- n_i is the concentration of the i -th element in the detonation products [mol/kg],
- ΔH_i is the heat of formation of the i -th element in the detonation products at standard conditions [KJ/mol],
- ΔH_{com} is the heat of formation of the composition from the chamber (explosive + detonator + air or explosive + detonator + argon) at standard conditions, when air is inside the chamber ΔH_{com} is equal to -173.58 J/g while in argon this value is equal to -134.83 J/g,
- m_{com} is the total mass of the composition (explosive + detonator + air or explosive + detonator + argon) and it is equal to 224.81 g when air is in the chamber or 286.42 g when argon is used,
- m_{exp} is the mass of the explosive inside the chamber (charge+detonator) and it is equal to 44.3 g.

The obtained plots of the theoretical explosion heat as functions of the activity of aluminum and the theoretical overpressure are presented in Fig. 8 and 9, respectively. Finally, the explosion heats are estimated as the heat of explosion corresponding to the experimentally determined QSP for each charge ($Q_{vest}=f(QSP)$) (Fig. 9). Once explosion heats determined, similarly, the percentage of aluminum consumption can be determined from the plots in Fig. 7 or 8.

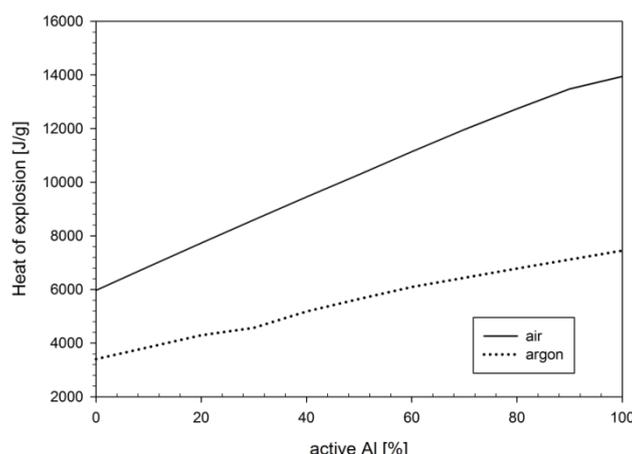


Fig. 8. Q_v variation with the activity of aluminum

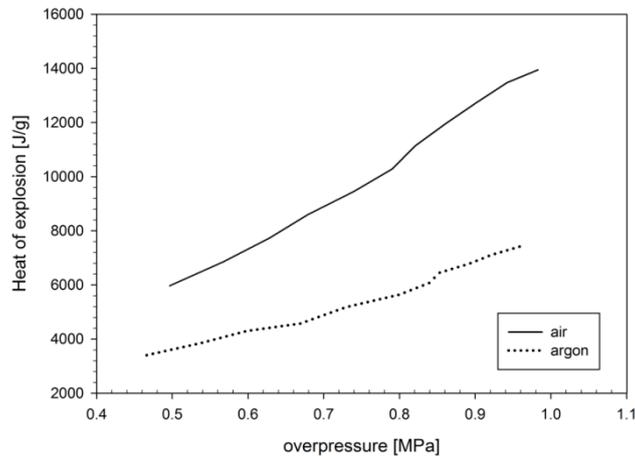
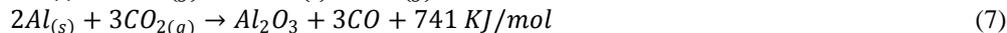
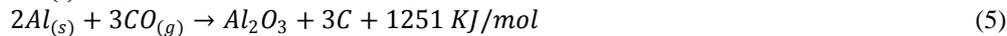


Fig. 9. Q_v variation with the calculated overpressure inside the chamber

Even the heat generated from the charges detonated in air is much higher than in argon (due to the lack of oxygen from air) in Fig. 8 and 9, surprisingly, the gap between the calculated theoretical overpressures is relatively small. This results from the differences in heat capacities of the gases filling the chamber. For the temperature range from 298.5 to 3000 K the heat capacity of argon in the chamber is constant and is equal only to 72.8 J/K, while the heat capacity of air increases from 129.3 to 181.6 J/K. Consequently, less heat is needed to increase the temperature of the detonation products in argon atmosphere and hence increase the overpressures. The plots of the theoretical explosion heat show that relatively large amount of energy is liberated during the explosion of TBX-A in air than in argon (Fig. 8). In fact, the main afterburning reactions of aluminum with the detonation products and oxygen from air can be represented by the following equations [5, 10, 29-33].



From the analysis of the composition of detonation products given by the thermochemical code for increasing percentage of active aluminum; it follows that, in air, the generated heat is mainly the consequence of an increase in the amount of alumina (Al_2O_3) in the detonation products, this alumina is the product of reactions of the active aluminum according to the oxidation channels (4-7). Consequently, the high heat generated leads to a high pressure and temperature inside the chamber. In argon, this energy is mainly provided by formation of aluminum nitride (AlN) which is the product of reaction of aluminum with nitrogen according to the reaction channel (8). This explains why the heat generated from the detonations in argon is much lower than heat generated in air atmosphere.

Table 4 includes the values of measured overpressures ΔP_{max} , the estimated explosion heats Q_{ves} and the aluminum consumptions Al_a for the investigated charges in air and in argon atmospheres. Calculated detonation energies E_d are also presented in the table. The energy of detonation was calculated using CHEETAH code. This energy is the sum of mechanical and thermal energies of detonation products. The mechanical energy represent the amount of energy available to do mechanical work and it is equal to the expansion work of detonation products and determined for the volume of detonation products corresponding to pressure equal to one atmosphere. Thermal energy represents the amount of energy locked up as heat of detonation products at the pressure of one atmosphere [27]. For E_d calculation, composition of detonation products was frozen at 1800 K on the isentrope beginning at the CJ (Chapman-Jouguet) point [34,35]. Two values of detonation energy are given in table 4, the first value is the lower limit of the detonation energy and corresponds to 0% active aluminum and the second one is the highest energy obtained for 100% active aluminum.

Table 4. Estimated explosion heats and aluminum consumptions for the investigated charges

Charge	ΔP_{max} [MPa]		Q_{ves} [J/g]		Al_a [%]		E_d [J/g]	
	air	argon	air	argon	air	argon	inert Al	reactive Al
TBX-11-A	0.79	0.66	10298	4556	50	29	3510	9740
TBX-12-A	0.77	0.60	9970	4351	46	22		
TBX-21-A	0.76	0.69	9784	4805	44	33		
TBX-22-A	0.79	0.61	10298	4371	50	23		

Actually, the term aluminum consumption indicates the effective combustion energy corresponding to a certain amount of aluminum and in which this energy contributed to the QSP inside the chamber. Evidences exists that in air aluminum reacts completely, however, part of this energy is used effectively to increase temperature and QSP inside the chamber and the other part is a late time energy which could be treated as not used energy. Unfortunately, from the Table 4 it follows that this late energy seems to be greater than the effective one. As expected, the explosions heats liberated by charges detonation were much higher when air was in the explosion chamber. These energies correspond to an active aluminum percentage varying between 44 to 50% for air and between 22 to 33% for argon in the chamber. This means that only part of the available energy was released during explosion and that significant amount of the energy could not transferred to heat in an adequate time to participate in the QSP. Some quantity of the energy could be liberated if all the aluminum fuel could react with adequate rate. The estimated explosion heats in argon atmosphere are higher than the detonation energy if we assume that aluminum is inert and much lower if we assume total reaction of aluminum. This relation confirms again that even argon has a diluting effect, small part of aluminum reacted, probably during the early stage of explosion when contact between the detonation products and aluminum powder was still enough to enable the aluminum afterburning reactions. While detonated in presence of oxygen from air, the charges generated explosion heats higher even than the detonation energy calculated for the active aluminum. However, it must be taken into account that the energy of the detonation was calculated assuming only the reaction of aluminum with detonation products and not the oxygen from air.

IV. CONCLUSION

The results of the current study gave an insight into the detonation and combustion of the composite thermobaric and enhanced blast explosives in a closed space. The used methodology enabled to deduce that only part of the energy available from the aluminum combustion was efficiently used during the composite charges confined explosions. This amount of aluminum is estimated to be a maximum 50% in air and 29% in argon. Unfortunately, still important amount of energy which could be potentially used during the explosions was not manifested in the form of growth parameters measured in the chamber. To increase the performances of the investigated composites, the combustion efficiency of the macroscopic granules can be more enhanced. The use of an energetic binder in place of Viton is an alternative to reach this goal. The use of activated aluminum powder during preparation of the composites can be another alternative to enhance the combustion efficiency. A lot of research and patents are devoted to this subject. The external aluminum oxide layer protecting the aluminum particle is the main problem. Modification of the reactivity of this oxide layer can be reach by using a mechanical activation of aluminium by inserting fluoropolymers inclusions or by coating the aluminum particles by a metallic layer of low combustion temperature such as magnesium. Metal hydrides such as AlH_3 or MgH_2 are also being tested in mixtures with explosives and they could be used in the macroscopic granules instead of aluminum powders.

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